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Boris S. Sokolov

Academician, Russian Academy of Sciences
Counsellor of the Presidium of the Russian Academy of Sciences

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Prospects for the Infrazonal (Microstratigraphic) Subdivision of Sedimentary Strata

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Abstract – Recent stratigraphic investigations imply that the microstratigraphic or infrazonal subdivision of ancient strata is feasible in the nearest future. Intrazonal markers of short-term events of the past include biotic, paleomagnetic, lithologic, paleoecologic, paleoclimatic, cyclic, and eustatic ones. These markers constitute a system of stratigraphically interchangeable markers (SIM), which allow us to subdivide zones into finer units of a different (usually regional and, in some cases, subglobal) scale. Their duration is estimated at tens or hundreds of thousands of years. A hierarchy and a nomenclature for the microstratigraphic units are suggested. Some examples of infrazonal subdivision (in particular, Cenozoic studies of the North Pacific) are given.

Key words: *Refined stratigraphy, zones, bioevents, datum planes, cyclicity, phenetics, and system of interchangeable markers.*

INTRODUCTION

The past decades have been marked by many advances in stratigraphy, which reflect tendencies that are clearly pronounced in the geological practice of most countries, including Russia. The most important trends in world stratigraphy and paleontology include the following: studies on ecosystems and event stratigraphy, the complex characterization of global and regional stratigraphic subdivisions, challenging problems of stratigraphic boundaries and stratotypes, Precambrian paleontological investigations, micropaleontological studies using nontraditional fossil groups, the application of a new technique to paleontological research and the encoding of paleontological and stratigraphic material, the unification of various stratigraphic codes and the development of stratigraphic nomenclature, and the elaboration of detailed stratigraphic scales. The latter is the subject of this article.

DEFINITION AND RECENT TRENDS OF STRATIGRAPHY

Many lengthy and obscure definitions of stratigraphy have appeared in the past decades. However, both the essence and goals of stratigraphy can be briefly defined on the basis of geological practice.

Stratigraphy is a branch of geology, which concerns, on the one hand, the classification of rock strata according to their time of formation and, on the other hand, the elaboration of a timescale of geological events. This is largely the "chronostratigraphy" that has recently converged seemingly opposite views on stratigraphy: the so-called "European" and "American" approaches (Zhamoida and Menner, 1974). Further considerations in this work are based on this understanding of stratigraphy.

Before discussing the problems of stratigraphic resolution, some recent trends in stratigraphy pertaining to these problems should be mentioned. First, recent investigations have revealed that the Standard Stratigraphic Scale compriseds three nonuniform parts (Precambrian, Phanerozoic, and Quaternary) (Menner, 1977). Each part is characterized by a specific unit resolution (10^9, 10^6, and 10^3 years, respectively). In the following, only the Phanerozoic part is discussed, but the problems of resolution are essential for all other parts of the scale on the corresponding levels.

There are specific methods for recognizing units of each of these parts. For instance, Precambrian subdivision is based on tectonic-magmatic cycles supplemented by biostratigraphic records. In the Phanerozoic, data on biological evolution are primarily used. For the Quaternary, climatostratigraphy is of prime importance. However, two facts should be noted. On the one hand, all units of the general scale are historical-geological ones, regardless of differences in age range and the leading method of their recognition. On the other hand, none of the leading methods can provide the necessary resolution for the above-mentioned parts of the scale. Therefore, worldwide stratigraphic practice made it necessary to unite various (bio-, magneto-, cyclo-, and climatostratigraphic and others) subdivisions and to substantiate them with integrated data (holostratigraphy, according to Walliser, 1986). This is the second trend in stratigraphy, which provided increased accuracy in the subdivision of ancient strata under the control of various methods. Thus, the idea of

the so-called "multiple" stratigraphy, comprising chrono-, bio-, and lithostratigraphies, which is commonly accepted without criticism, appears to be refuted. Meanwhile, as was correctly stated in the final chapter of *International Stratigraphic Guide* (1976, p. 96), "chronostratigraphic classification, which utilizes information available from all other kinds of stratigraphic classification, stands out as an ultimate goal of stratigraphy." In other words, there is a single "stratigraphy" that uses either one of these methods or their combination, depending on the situation.

The third trend in stratigraphy is the so-called "event" stratigraphy, the objective of which is the regional or subglobal correlation of geological events (Ager, 1973). This objective has actually been taken into account in the elaboration of all stratigraphic schemes. It has long been known that the best scale is one that is based on geological history. However, only recently has the intentional "catching" of traces (signals) of past short-term events promoted both the causal line of stratigraphy and higher stratigraphic resolution.

It is with these listed stratigraphic trends (recognition of three parts of the stratigraphic scale, complex unit characteristics, and relation to geological events) in mind that the problems of more refined stratigraphy should be discussed.

Zonal Stratigraphy and Its Development

In principle, higher resolution is an old problem of stratigraphy. Some aspects of this problem were discussed by Menner and myself (1986). The Paris session of the IGC in 1900 accepted a system and a series as the finest units of the Standard Stratigraphic Scale. Not only zones, but even stages were not considered as subglobal units (they were referred to regional ones). It took 70 years before first a stage, and then a zone (chronozone) were included in the Standard Scale. The 1960s and 1970s were a time of bloodless revolution in stratigraphy, when zones were readily recognized in almost every Phanerozoic system (the Paleozoic comprises up to 130; the Mesozoic, 145; and the Cenozoic, 45 zones) (Gladenkov, 1991). The subsequent wide usage of zones was, in particular, due to deep-sea drilling, which showed that zonal subdivisions can be traced over vast areas of the earth surface (the Pacific, Atlantic, and Indian oceans and many continents). At present, nearly all national stratigraphic codes accept a zone as the finest unit of the stratigraphic scale. Establishing a zonal unit whose duration is estimated at 0.2 - 3.0 m.y. (fantastic time resolution!) is the greatest advance in geology, comparable, for example, with new global tectonics.

However, this brings up the following question: What next? Is it possible to make stratigraphic schemes more detailed? Is there a need for more detailed schemes? It should be pointed out that geological practice has long shown an interest in high-resolution schemes. First, these schemes are needed for large-scale geological mapping and the interpretation of drilling data as well as for prospecting for hydrocarbon traps and mineral deposits. Second, these schemes are necessary for elaborating detailed paleogeographic schemes, making reconstructions, better understanding trends and mechanisms of the biosphere evolution, and prognosing environments of future decades and centuries. Third, refined stratigraphy can contribute greatly to fundamental geological investigations.

These problems have drawn increasing attention, especially from practical geologists. In the early 1990s, special meetings were held in the USA and Canada; materials on drilling, logging, and seismic investigations served as a basis for discussing the recognition of finer stratigraphic subdivisions, which cover periods of hundreds of thousands of years and less, and the determination of local catastrophic events and subglobal eustatic oscillations (these oscillations may be related to glacioestasy, e.g., the Quaternary ones, or they may not be related to it, e.g., the Late Cretaceous ones that were recorded in Australia and South Africa). It was concluded that progress in geological works, particularly in oil prospecting, could be achieved through the optimal application of all available facilities and methods rather than a new technique (Armentrout and Perkins, 1991; Posamentier and Leckie, 1992).

The problems of high-resolution schemes were thoroughly considered at the latest IGC session in Kyoto, 1992. They were the subject of many reports concerning both quantitative methods and detailed paleogeographic reconstructions.

Nevertheless, there is currently no comprehensive analysis of this stratigraphic line in regard to the significance of different methods for the attainment of higher stratigraphic resolution, the hierarchy of the suggested finer units, and examples of successful microstratigraphic subdivision.

Meanwhile, Russian stratigraphers have accumulated a great amount of interesting material.

Zone Types

Because finer stratigraphic subdivision is related to zones and developed on the infrazonal level, it seems expedient to briefly mention the types of zonal units. According to the Russian *Stratigraphic Code* (1992), there are two types of zones: a zone (chronozone) as a unit of the Standard Stratigraphic Scale, which is subordinate to a stage, and a lone (local zone), which is subordinate to a horizon and is a unit of a regional scale. These types of zonal units determine the specific character of an infrazonal subdivision in each particular case, although they are similar in principle.

In some countries, stratigraphic practice uses the subdivision of zones (chronozones) into subzones or zonules. Notions of these units are usually conventional

(the exact definitions are not given, as a rule), but the published examples and data suggest that they imply parts of zones that are characterized by certain facies complexes of local, but not subglobal, distribution.

Attempts to subdivide lones into subzones are being made as well, but they are based on indistinct features. The mentioned *Code* ranks as lones those beds with geographic names recognized by lithologic or paleontologic characteristics.

Chronozones and lones are referred to principal stratigraphic units with complex substantiation. However, there are a number of zonal categories ranked as special units of particular (biostratigraphic) substantiation. These are biostratigraphic zones, which can be subdivided into subzones, and beds with fauna (flora) as an auxiliary unit. A biostratigraphic zone can be represented by zones of various species, whose peculiarities in distribution and combinations form the basis for recognizing chronozones and lones. These are biozones (taxon-range zones), concurrent-range zones, phylozones, interval zones, epiboles (maximum taxon abundance), assemblage zones, and others. In some cases, they permit some parts in zones and lones to be singled out (e.g., within a lone there may be a stable level of an epibole, which divides it into two or several parts). This especially concerns zonal units that represent provincial or local zones in terms of their area of distribution. It is in a paleobiogeographic province or even an area, which commonly corresponds to an ancient sedimentational basin with a specific geological history (an isolation degree, changes in sedimentation and depth enviroments, etc.), that the recognition of certain levels and markers characteristic of various biostratigraphic zones is an actual procedure for present stratigraphic investigations.

PROBLEMS AND METHODS OF MORE REFINED STRATIGRAPHY

The elaboration of high-resolution stratigraphic scales suggests some topical questions concerning the following: (1) the methods and procedures that should be used, (2) the spatial extent of the recognized finer units, and (3) the duration of these units. The geological time can mainly be inferred from linear unidirectional irreversible processes, which are studied by two methods: the isotopic dating method, based on the radiometric decay of isotopes, and the paleontologic method, based on biological evolution. Despite considerable errors in age determination by the first method and relative datings by the second one, these methods enable us to create a geochronological framework and to outline the chrons used in geological practice. They may be supplemented by other methods related to rhythmic-periodic processes, which are reflected in sedimentary cycles, banded clays, and so on. However, these data, as well as lithologic, seismic, and paleomagnetic records, are not indicative of geological time (in the true sense of the word) or of the age assignments of stratigraphic subdivisions provided by isotopic dating and paleontological methods. They are often helpful in correlation in that they offer many various markers, but their significance increases noticeably when these markers are related to the actual time scale.

WAYS OF OBTAINING HIGHER RESOLUTION SCHEMES

As mentioned above, current geological practice develops the feasible ways of increasing stratigraphic resolution. Materials related to paleontological and some other methods are summarized below.

Paleontological Method and Infrazonality

The possible subdivision of zones (chronozones) and lones using various biostratigraphic zones was discussed above. Herein, it should be stressed that these zones, like other paleontological markers, are reflections ("traces") of certain geological phenomena, i.e., relatively short-term bioevents, which are evident from geological records and, thus, permit microstratigraphic subdivision. What are other paleontological tools for revealing traces (or "signals") of these events?

First, new fossil groups can be used. The set of groups used in biostratigraphy increases continuously (it will suffice to mention the recent utilization of conodonts, nannoplankton, dinocysts, and other microfossil groups, which have contributed greatly to the development of zonal stratigraphy).

Second, new approaches to biostratigraphic subdivision and improvements in the traditional methods can be elaborated.

Third, the revision of our notions of the morphology and taxonomy of individual fossil groups may result in different interpretations of biostratigraphic data.

The first item needs no explanation; I shall dwell on the other two.

STRATIGRAPHIC RESOLUTION ON A PALEONTOLOGICAL BASIS

Bioevents. In principle, any discrete phenomena of biological evolution that are evident from geological records can be used for the finer subdivision of ancient strata. However, a scale of the phenomenon is essential. For example, the middle Miocene climatic optimum, estimated at 0.5 - 1.0 Ma, is useful for the recognition of a stage rather than for infrazonal subdivision; but studying climatic oscillations with regard to this optimum can help to distinguish finer units.

According to Gretner (1984), an event (not just a biotic one) should span 0.01 of the considered time interval. Hence, an event of a geological period lasts some hundreds of thousands of years. For our purposes, however, events that are shorter than zonal categories

and correspond to their parts (including intrazonal markers) are more important.

There are some different classifications of bioevents. The classification of Kauffman (1986) distinguishes eight types of events: (1) events of punctuated evolution (the spasmodic appearance of a new taxon of species rank), (2) population bursts, (3) a short-term increase in the productivity of a basin, (4) immigration and migration, (5) ecologic events (drastic changes in biological community structure), (6) regional colonization (occupation of vacant biotopes), (7) mass mortality (caused by abiotic factors), and (8) mass extinction (global disappearance of more than 50% of taxa over a short period). Any of these bioevents can be recorded for use in finer subdivision.

As they are the subject of a particular study, the causes of bioevents and trends and the nonuniformity of evolutionary processes are not discussed herein. We are dealing with the consequences of these events, which are reflected in taxa or assemblage changes and in the occurrence of paleontological markers in sections. As far back as the 1940s, Rauzer-Chernousova and Kulik (1949) put forward the idea of the periodic evolution of ancient assemblages, having used the Carboniferous foraminifers of the Russian platform as an example. At present, periodicity is understood as various cyclic changes in assemblages. These are either some taxonomic changes related to the evolution of ancient groups (evolutionary stages) or the redistribution of various forms, which is characteristic of short rhythms and caused by paleogeographic factors. Redistribution is often responsible for marker occurrences within zones.

Polytaxa subdivision. In practice, there are different ways of subdividing zones. One of them is related to intensive zonal studies. For instance, in the 1950s, a thorough study of planktonic foraminifers allowed V.G. Morozova to distinguish three zones and five subzones in the Danian. These investigations were highly appraised at the XXI session of the IGC. Another way is related to the simultaneous usage of several paleontological groups. In actual practice, some zones defined by an individual group, e.g., foraminifers, can include finer zones based on other thoroughly studied fossil remains, or they can show intervals substantiated by boundaries that are established by means of other groups. An example is provided by the Paleogene and Neogene stratigraphic scale based on tropical planktonic foraminifers. In the 1970s, this scale was supplemented with zones defined by nannoplankton and siliceous organisms. This allowed some additional boundaries identified by other groups to be outlined within the foraminiferal zones. Here, we are dealing with polytaxa subdivision, to which little attention has been paid. For example, four additional nannoplankton levels (five zones) were identified within two Paleocene zones of *Globorotalia angulata* and *G. pseudomenardii* in the Pacific and Atlantic oceans (Krasheninnikov, 1978). Similarly, the noncoincidence of the boundaries of foraminiferal, nannoplankton, and radiolarian zones can produce some distinct levels that subdivide many of the Eocene, Oligocene, Miocene, and Pliocene foraminiferal zones.

Datum-planes and interdats. Many recent publications analyze the levels of the first and last occurrence of various taxa in sections. These levels are often helpful for attaining more details in stratigraphic schemes. This approach allowed Kauffman (1969) to increase the biostratigraphic resolution for the Cretaceous strata of North America several times over what had been attained earlier. In his opinion, nearly 100 very reliable zones and boundaries and 150 less reliable boundaries can be distinguished in the interval of 38 Ma. Another well-known example concerns the recognition of up to 80 finer units within 4 - 11 conodont zones in the Middle-Upper Ordovician of North America (Sweet, 1984). Barron *et al.* (1985) carried out an interesting investigation on the finer subdivision of Neogene oceanic sediments. They revealed 175 levels of the first and last occurrences of some planktonic forms; in the Miocene (about 20 m.y.) 72 of them were correlated with the paleomagnetic scale. Attention was paid to the stability of both separate levels and their combinations. The time intervals between these levels appear to have been estimated at some hundreds of thousands of years, i.e., they are comparable to the time ranges of the Quaternary units. Some new detailed schemes of the stratigraphic distribution of individual taxa (biozones correlated precisely with geochronological and paleomagnetical scales) have been suggested recently. One of them was compiled for Neogene diatoms and used during ODP Leg 145.

Datum-planes are commonly used now, even though the beds between them are not yet named, although the term "dated intervals," or "interdats," was proposed (Menner and Gladenkov, 1986). They may be or may not be contiguous to each other, but this largely depends on the thoroughness of material analysis. Some of them (or their "packages") are probably traceable throughout wide areas, while others are confined to separate belts and provinces. It is urgent to form a data bank for datum-planes and interdats to control their stability and introduce them into practice.

New approaches to the taxonomy of paleontological groups: Phenetics. One potential for the finer subdivision of ancient strata lies in the development of new approaches to the morphology and taxonomy of ancient organisms and the revision of old approaches. The usage of new equipment (the scanning electron microscope and others), which enables us to investigate in a new way the inner structure of, for example, diatom frustules, radiolarian skeletons, molluscan shells, etc., makes it necessary to revise some taxonomic classifications, change some generic and species characters, and identify new taxa. It is not an exaggeration to say that this approach together with quantitative methods,

which are stimulated by computer usage, marks a new stage in the study of paleobiota. This enables us to revise the customary volumes of taxa (especially species); identify new, finer taxa; and, consequently, to outline some additional resolution levels. The introduction of the phenetic system can serve as an example. A paleontologist can define species variability by processing statistically large amounts of fossil remains, which represent paleopopulations. Analysis of variations in characters, especially discrete ones (phenes), which are fixed in time and space, can reveal some trends and stages in microevolution. Abundant paleontological material, sampled bed-by-bed, represents unique records of natural experiments that lasted for hundreds of thousands and millions of years. This material exhibits the early evolutionary stages, the flourishing and extinction of species, or the appearance of new species. This enables us to identify paleopopulation forms that change throughout the sections. These forms draw little attention because they are commonly believed to fall within the range of specific variability. In the 1970s, Sarycheva and Yablokov (1973) and some other researchers demonstrated the application of phenetic methods to paleontological investigations. In particular, Krasilov (1980) proposed that phenozones be recognized as units based on different morphological characters. Regretfully, this approach was not widely accepted, but after quantitative methods are introduced into practice, it will afford new opportunities for the detailed identification of fossil forms, which, in turn, will provide us with additional levels and markers within horizons and zones of different scales.

The identification of morphs and morphotypes of individual species, which are variable in time, appear promising for refined stratigraphy.

Some examples of species "splitting" have already been discussed in the literature. They concern both macro- and microbiota. For instance, two Mitilidae species from the Cretaceous of North America were recently separated on the basis of a number of characters into nine morphs, which are persistent in the "populations" (over a bed extension) and separated in time (in successive beds) (Kauffman, 1986).

The morphotypes of some late Cenozoic species of planktonic foraminifers from the Atlantic and Indian oceans were recently identified on the basis of variations in the stable isotopes of the shell substance. The number of such examples could be increased, and we should not neglect this approach. It should also be stressed that finer subdivision on a paleontological basis can be achieved by advances in the biological sciences: genetics, biochemistry, ecology, and biogeography. Ecostratigraphy combined with paleopopulation analysis will be of great importance. Hemofossils (as traces of amino acids) have already been used to distinguish some marker levels (e.g., in the Pliocene-Pleistocene of Alaska and Chuckchee Land).

Infrazonal Subdivision by Nonpaleontological Methods

Markers related to past abiotic events are discussed in this section. When found within zones, these markers permit subdivision, and the task is to estimate the temporal extent of these markers and to define their exact stratigraphic position and spatial distribution scale. Whereas zones usually correspond to a time interval of 0.2 - 3.0 m.y., intrazonal markers are naturally "shorter." Some of them are discussed below.

Paleomagnetic markers. There are two types of these markers. The first type includes excursions (anomalies), estimated at a few thousands of years, and reversals (polarity changes), which are 5- to 40-ka long. The markers of the second type are magnetozones with a duration of less than 2 or 3 m.y. (orthozones are 5 - 0.5; subzones, 0.5; and microzones, less than 0.5 m.y.).

Lithologic markers. There are different kinds of these markers. Most of them have regional significance, but some are used in the interregional scale. The latter include ash beds and thin apotuffaceous bentonitic interbeds (they are sometimes even numbered). These markers are especially helpful when characterized by features, which make them distinguishable in different sections. This can be well-illustrated by the Cenozoic sections of the North Pacific.

Among lithologic markers, there are kerogen-mineral laminae (a few millimeters thick), which are characteristic, for example, of the Mesozoic shales enriched in organic matter and the carbonates of New Mexico as well as the coccolite-kerogen beds of the Toarcian shales of Germany (Hallam, 1984). N.G. Muzylev recently distinguished beds enriched in organic matter and related to anoxic events in the Paleogene of Ciscaucasia and Middle Asia. Some of these beds are thin and occur within nannoplanktonic zones. For instance, there is a distinct bed at the boundary between the nannoplanktonic subzones CP8a and CP8b (according to Bukry's scale). Black shales indicative of anoxic events of the past (at the Frasnian-Famennian boundary and elsewhere) are in wide use as regional and global markers (Walliser, 1984).

Recently, attention has been drawn to other markers: turbidites, inundites (flood deposits), tempestites (storm deposits), tidalites (deposits of high tides), homogenites (beds with homogenous structure), unifites (homogenous silty clays), seismites, coquinas, and others. (*Cyclic* ..., 1982). Some fossil soils or pedologic horizons can be distinguished as well. The Middle Asian Eopleistocene shows about 10 horizons of fossil soils, and attempts have been made to correlate them with the isotopic stages identified in oceanic sediments.

Other markers of different origin can be mentioned. Among them there are beds with a definite set or a high concentration of various metals, e.g., metals of the platinum group, particularly iridium beds, regardless of their origin (volcanic or impact).

Hiatuses. Some short-time sedimentary hiatuses can serve as markers. For example, some Miocene oceanic sequences exhibit up to eight hiatuses corresponding to parts of zones. Hiatuses with a duration of 0.2 or 0.3 m.y. a were recorded in the Pliocene of east Kamchatka. These data are very helpful in the finer subdivision of ancient strata.

Paleoecologic markers. Bedding variations as well as changes in paleoecologic groupings in a section and the character of fossil burial can also serve as regional markers. The types of paleoecologic markers were comprehensively discussed by Gekker (1957), who noted their occurrence in various facies ranges. To some extent, his views were transformed into ecostratigraphic ideas of ecosystem changes reflected in various paleoecosystems. Because the biota is the most sensitive element of these systems, providing the best evidence for various abiotic events, biotic changes (especially of dominants) accompanied by lithologic ones throughout sections provide distinct stratigraphic markers. For example, short-term breaks in oceanic circulation are known to have resulted in the appearance of ecological environments that were fatal for marine biotas (phenomena such as "red tides," El Nino, and others).

Attempts are now being made to develop a specific nomenclature and classification to be used in ecostratigraphy. Krasilov (1980) suggested that ecozones based on different biotic communities are the principal units of stratigraphic classification. Their successions are thought to be amenable to causal analysis; however, they have a limited application, having been dissolved in traditional zones and other stratigraphic subdivisions because of the insufficient study of their characteristic features. However, some ecozones appear to be real units that are finer than the traditional oppel-zones (e.g., the ecozones defined by the Triassic plants of eastern Australia, the Triassic-Jurassic floras of western Siberia, and others).

Paleoclimatic markers. Markers related to paleoclimatic events have become very popular now. Annual banded clays have long been their classic example. In the early years of this century, de Heer substantiated a teleconnection of these deposits (a correlation between the clays of Eurasia and North America). In addition, there are other signs of paleoclimatic changes, which include changes in lithology, sedimentary and diagenetic textures, and biotic associations-climatic indicators (particularly palynoassemblages). For example, more than 20 palynozones of different ages were recognized in the interval of the Akchagylian - middle Pleistocene of eastern Transcaucasia and western Turkmenia. They are characterized by alternating palynoassemblages of mezo- and xerophillous types reflecting pluvial and arid environments, respectively (Filippova, 1994).

Isotopic stages with a duration of 10 - 80 ka identified by the oxygen isotopic dating method (Shackleton and Opdyke, 1977) have also been widely used for the last 20 years to mark climatic fluctuations. There are some classifications of Quaternary units developed on the basis of climatostratigraphic data. They were suggested in the 1970s - 1980s by E.V. Shantser, I.I. Krasnov, and K.V. Nikiforova (1973); V.A. Zubakov (1978); V.V. Menner (1979); and others. The Russian *Stratigraphic Code* (1992) indicates the following units based on paleoclimatic records (in descending order): division, link, and step as general units and climatolith, stadial, and "nasloi" as regional ones. Attempts are being made to recognize these subdivisions in the Neogene.

It is important that all of them, except for division, correspond to time intervals varying from 120 - 300 k.y. to a few tens of thousands of years. The finer units (i.e., stage, stadial, and oscillation) range in age from 7 - 12 to 1 k.y. This means that their identification within zones (and divisions) may help in infrazonal subdivision. In any case, superclimathems, 100- to 300-k.y. long, have become recognizable in the Neogene.

Cyclic markers. This approach to finer subdivision is realized in cyclo- and rhythmostratigraphic investigations, which at first encompassed banded clays and coal- and salt-bearing strata, and later encompassed formations of other types. Rhythmostratigraphic categories have been long discussed in Russian literature. In his classic books on flysch, Vassoevich (1948 and others) reviewed many specific features of cyclostratigraphy and, significantly, noted a possible teleconnection between finer units.

Some publications by Popov and coauthors (1979), Zubakov (1978), and others dealing with various aspects of cyclic sedimentary processes are worth mentioning. Similar investigations are being carried out in other countries (*Cyclic* ..., 1982). It was revealed that rhythmic sequences may have been formed as a result of event changes or gradual periodic changes in sedimentation (periodites or small cycles). Sedimentary cycles may or may not provide information on the geological time. Some investigators derive the rhythmic occurrence of strata from global (in particular, the orbital cycles of the Earth in various periods, e.g., 21 000, 41 000, and 100 000 years) or local (e.g., tectonic regional movements) factors.

Cyclic markers that can help in obtaining higher resolution schemes are of particular value. The publications of Gekker (1957) and Sorokin (1978) on the Devonian of the Russian platform substantiated the recognition of cyclic units of various ranks by paleoecological and paleogeographical methods. Sorokin distinguished within the Frasnian the cycles of orders VII - XII: the cycles of order VII correspond to substages, cycles of order VIII correspond to horizons, cycles of order IX correspond to beds with geographic names (14 rhythms), cycles of order X correspond to members (36 rhythms), and cycles of order XI and XII correspond to beds of some structural-facial zones.

Recently, attempts were made to estimate the duration of various cyclothems on the basis of isotopic age

determination, sedimentation rates, and so on. For example, Afanas'ev (1987) considered the hierarchy of cyclothems (or stratons) in which units of class VIII span 800 k.y., those of IX span 190 k.y., and those of X span 40 k.y. Mesocycliths of these classes may be useful for microstratigraphic subdivision. Some cyclothems are traceable over a few hundred and even thousands of kilometers.

Seismostratigraphic and eustatic markers. In the 1970s - 1980s, the so-called "lithological clock," or eustatic scales, i.e., scales of sea level oscillations allocated geochronologically, were constructed with regard to seismostratigraphic records (Vail *et al.*, 1977). Later, any cycles of sedimentation recognized in various ancient basins and originating from sea level oscillations of different scales were related to this scale. If the correlations are correct, these cycles have a definite chronostratigraphic position. This concerned at first large cyclothems estimated at hundreds and tens of millions of years and, later, smaller ones: cycles of order III (1 - 10 m.y.) and orders IV and V (10 - 1000 k.y. and less). Although there is no established nomenclature yet for these units, attempts have long been made to develop their hierarchy [e.g., a system (synthem–seismopackage–seismoquant) was suggested along with the recognition of marker seismohorizons]. Identified in a section, these cycles provide distinct marker levels. However, eustatic cycles are rather difficult to reveal because it is often impossible to specify the causes (tectonic, sedimentary, or eustatic) of cyclicity and to define the precise stratigraphic position and duration of the cycles. Regretfully, the recognized cycles are often related to the "lithological clock" without sufficient grounds. Nevertheless, some experience of using seismostratigraphic data to make stratigraphic schemes more detailed has been gained. In some cases, data on both horizontal complexes and progradational successions are utilized. For instance, the Neocomian sequences of the western Siberian plate show more than 20 clinoforms corresponding to parts of stages and zones. In addition, attempts are made to subdivide the cycles into three parts related to the beginning of a transgression; the high sea level stand, which is usually short-term; and its rapid lowering. There are some finer oscillations established with regard to these.

HIERARCHY AND NOMENCLATURE OF FINER UNITS

The problem of the hierarchy of infrazonal units is both simple, because various informal units have long been used, and complicated, because there is no single approach to their classification similar to that developed for larger units. Experience shows that finer subdivisions distinguished locally on a lithologic basis are more commonly used. The Russian *Stratigraphic Code* recommends the following units: stratum–member–bed–marker horizon. But their duration and relation to subdivisions distinguished by other methods are not discussed.

If they really exist, the cyclicity of geological phenomena suggests some periodical changes in processes of different character and rank, which occurred during an irreversible development related to cosmic processes and the evolution of the earth shells. From this standpoint, climato- and cyclostratigraphic categories may reflect different aspects of the geological processes in the evolution of the earth shells. Naturally, it is tempting to correlate sedimentary-cyclic and climatostratigraphic categories and to establish some parallel unit orders. Certainly, this is not a simple thing to do, although units of these two categories are, in most cases, manifestations of the same geological processes (or, to be more cautious, causally related processes). They may take the same position in the chronostratigraphic scale, but this needs to be confirmed in each individual case. In the mid-1980s, Menner and myself (1986) made an attempt to establish two parallel orders of cyclostratigraphic and climatostratigraphic units of particular substantiation. In addition, a third category, involving general microstratigraphic units of complex substantiation, which reflect the main features of sedimentary strata, was outlined. It is as if they summarize or incorporate the above units, thus being the resulting ones. They can be singled out even when cyclo- or climatostratigraphic characters are indistinct (although the definite succession and rank of these subdivisions are generally perceptible) or when some of these units are correlative with single cyclo- or climatostratigraphic categories.

Table 1 represents a variant of the relationship between these units. There is a correspondence between two or three units of each category, but that still cannot be proved for the finer units. Three types of subdivisions – general microstratigraphic (m), cyclostratigraphic (c), and climatostratigraphic (cl) – are briefly characterized below.

Beds with geographic names, or "svyazka" (the term was suggested by B.M. Keller), are a microstratigraphic unit subordinate to a lone and "summarizing" a cyclothem (c) and link (cl). A cyclothem (the term was introduced by Wanless and Weller) corresponds to a compound sedimentary cycle. A link corresponds to a large climatic rhythm.

The finer units comprise a *member* (m); a *cyclomember* (c), as a large part of the cyclothem; and a *superstep* (= *circle*) (cl), representing a "warm" or "cold" part of the link. In turn, they are subdivided into finer units of the third order. These are the following: *cyclith* or *cyclolith* (the terms of N.F. Balukhovskii and Yu.N. Karagodin) (c), which spans a uniform part of a cyclomember; *step* (cl), which corresponds to a single glacial or relative warming or cooling event; and *package*, which is a general unit (m). It is impossible to fix any finest units yet.

Table 1. Finer stratigraphic units

Subglobal	Regional					
Stage, substage	Regiostage			Horizon		
Chronozone	Lone (local zone)			Division		
	microstratigraphic		cyclostratigraphic	climatostratigraphic		
Glon	Beds (Dilectus)		Cyclothem	Link		110 - 300*
Interevent	Member (Membrum)		Cyclomember	Superstep Circle		60 - 200
	Package (Fundus)		Cyclolith	Step	Isotopic stage	10 - 70
Event	Bed Sheets Sims		Bed Sheets Sims	Stage Stadial Oscilation		5 - 12 1 - 5 1

* Duration, k.y.

The suggested hierarchy and terms may be subject to objection, and it is not certain that these units will be introduced into practice at once. Some of them are still informal and specifically Russian. Their international usage may meet many difficulties. A few years ago, Latin names were proposed for some general microstratigraphic units: beds – dilectus (Lat. – set), member – membrum (member), and package – fundus (basis) (see Table 1). Their rapid practical utilization can hardly be expected.

It is very important to estimate the duration of infrazonal units, even if approximately. At present, reliable materials are available concerning the climatostratigraphic subdivisions discussed above. Each unit appears two or three times longer than the next subordinate unit. The fixation of cyclostratigraphic categories seems to be premature despite some experience with their age estimation. Their possible correspondence to climatostratigraphic units (when proved) permits their duration to be estimated on the basis of the age ranges of the latter.

Certainly, the suggested scheme is one possible version of infrazonal unit hierarchy. There may be other variants that should be discussed.

INFRAZONAL SUBDIVISION OF THE FAR EAST NEOGENE

The recognition and usage of microstratigraphic subdivisions are illustrated below by the example of investigations of the Neogene sequences in the Kamchatka–Sakhalin region. This region is a very complex geological object in the transitional zone from the Pacific Ocean to the northeastern Asian continent. It is mainly formed by deposits of the geosynclinal type, characterized by a great thickness, complicated lateral changes, volcanic rocks, etc. (Gladenkov, 1988). A bed-by-bed analysis of the Neogene mollusks, foraminifers, and diatoms from eastern Kamchatka together with paleomagnetic and isotopic studies suggested a finer subdivision of these deposits. The analysis of fossil remains was based on the total number of species in every bed, dominants, appearing and disappearing forms (datum-planes), the percentage of extinct taxa, the paleoecologic and paleogeographic confinement of species, the percentage of endemics, and so on. This approach permitted a detailed para- and orthosubdivision based on both benthic and planktonic fossil groups. The combined stratigraphic analysis of different groups (in particular, mollusks and foraminifers) makes the stratigraphic schemes more detailed and reliable (for details, see Gladenkov *et al.*, 1992; Gladenkov, 1994).

In total, 42 beds with mollusks (M) and 21 beds with foraminifers (F) were distinguished within six or seven Neogene horizons of eastern Kamchatka (Karaginskii Island), which correspond to 14 diatom zones. They were united into 15 and nine members with fauna, respectively. Boundaries of many beds and members M and F coincided well. A combination of these beds and members identified by different groups provides cumulative or complex paleontological characteristics of many subdivisions. The duration of the beds amounts to 0.03 - 0.09 m.y., and that of the members, 0.12 - 0.35 m.y. The age estimation took into account paleomagnetic data, isotopic datings, isochrons marking the diatom zonal boundaries, and the sedimentation rate. In addition to the beds and members, up to 15 levels of different reliability be can used. These levels mark the appearance of individual taxa in the strata. The levels of paleomagnetic reversals (more than 20 in the upper part of the section), ash tuff interbeds (up to 13 - 15), hiatuses (six relatively large ones), and others can also be regarded as markers. As a result, every member appears to be comprehensively characterized by paleontological, lithological, magnetic, and other records.

Similar beds with mollusks and foraminifers were recognized in the Neogene of western and northeastern

Kamchatka. Many stable and similarly successive beds are traceable in Kamchatka over a distance of 300 - 800 km. The combination of "stability" and "similar succession" justify the recognition of these beds as a straticraphic unit. Some of these beds and members were distinguished in Sakhalin and Alaska.

The investigations allowed us to obtain high-resolution stratigraphic schemes, which are currently used in geological mapping, and to proceed to a detailed reconstruction of the short-term paleogeographic events.

A SYSTEM OF STRATIGRAPHICALLY INTECHANGEABLE MARKERS (SIM)

In summary, it should be noted that recent stratigraphic investigations exhibit numerous examples of successful infrazonal subdivision of ancient strata. This was promoted by recognizing within zones and lones finer units of different types (beds with fauna, high-order cycles, paleoclimatic units, and others) as well as various markers to subdivide zones into two or several parts (Table 2). Subdivison can be achieved by using the appropriate terms (e.g., lower and upper parts or undertuffaceous and overtuffaceous parts of a zone, normally magnetized part, and so on) and by developing the nomenclature of local and wider scales. In principle, two plane markers of any kind allow us to single out finer volumetrical parts of chronozones (as microhorizons, interdats and others). The aforesaid shows that infrazonality is well-substantiated in many cases.

However, it should be understood that the reclassification of regional microstratigraphic units requires great precaution, because their practical usage is proven to be reliable only on a regional scale. Nevertheless, some of them are already used on a global scale as well (e.g., paleomagnetic reversals and episodes, paleoclimatic optima, and others).

The summarized data on infrazonal units and intrazonal markers of various origins suggests that they reflect short-term, often spasmodic (catastrophic) events. Most of them are classified as local or regional (traceable in separate basins and provinces), but some appear to be of subglobal character (in oceans and continents). In some cases, the markers may coincide in time (e.g., paleoclimatic-eustatic ones), but most often, they are asynchronous (e.g., lithologic-biotic-paleomagnetic and others), and the number of markers in a zone or lone increases.

Certainly, common sense should be exercised when using markers: their occurrence, the possibility of utilizing them (to recognize and to trace), and their temporal and spatial relationships (stability of their stratigraphic position and their spatial distribution and interchangeability) require objective analysis.

Special attention should be given to distinguishing these markers within zones, i.e., within definite time limits. The interchangeability (or substitution) of features throughout sections is what should draw the attention of stratigraphers.

Table 2. System of stratigraphically interchangeable markers (SIM)

Subdivisions of stratigraphical scales		Markers							
		biotic	paleo-magnetic	lithologic	hiatuses	paleoecologic	paleoclimatic	cyclic	eustatic
	12	•							
	11	•							
	10	•							
	9	•							
Zones	8	•							
Lones	7	•							
(0.2 -	6	•							
3 m.y.)	5	•							
	4	•							
	3	•							
	2	•							
	1	•							
	0	•							

• – marks (dates) on the timescale of geological events.

Indeed, this implies the compilation and usage of a calendar of short-term geological events and the definition of the reliability of their traces and their exact stratigraphic position within chronozones.

Thus, high-resolution schemes can be obtained by means of a system of interchangeable (or substituting) markers (SIM), which reflect short-term geological events. Every SIM is characterized by specific unit resolution and a spatial scale. Naturally, the number of markers in a SIM of local or regional stratigraphic schemes will be greater than that of interregional and subglobal scales. It is very important to find markers to correlate various SIMs.

CONCLUSION

At present, one of the main goals of stratigraphy is to analyze the experience that has been gained in increasing stratigraphic resolution. Regretfully, few sections have been subjected to infrazonal subdivision and long-distance correlation. In addition, there are too few specialized methodical publications and discussions that deal with this subject. The classification and terminology of finer units receive little attention. But on the threshold of the 21st century, geologists must realize the need for new stratigraphic schemes that are more detailed and event-based. Integrated methods and new procedures for stratigraphic analysis may afford new opportunities and promote microstratigraphic investigations. A similar thing happened in the 1960s, when new sophisticated equipment for seismostratigraphic research made it possible to identify both "sharp" and "faint" boundaries corresponding to acoustic rigidity ranges of 10 - 50% and 2 - 3%, respectively. Recently, the boundaries can be identified in 50- to 100-m intervals and even more frequently than one boundary per one kilometer of depth, as earlier.

Stratigraphy is a fundamental part of geology due to the geohistorical concept, which introduced the notion of time into the analysis of geological events. As a branch of geology, based on fundamental geological principles, stratigraphy develops in accordance with its own essence. The microstratigraphic subdivision of sedimentary strata is a reflection of this essence. Undoubtedly, this stratigraphic trend will be developed further.

"To have scales with unit resolutions of tens of thousands or even a few thousand years is too alluring a prize for stratigraphers to be relinquished" (Menner and Gladenkov, 1986, p. 17).

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Geology and Isotope Dating of the Sumian–Sariolian Lower Proterozoic Volcano-Plutonic Complex in Northern Kareliya, the Paanajarvi–Tsipringa Structure

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Abstract – The rocks of the Paanajarvi–Tsipringa structure, northern Kareliya, were studied by the U-Pb method using zircons to obtain geochronological datings for the following: plagiomicrocline granites (2710 ± 110 Ma), which intrude the granite–gneisses of the Archean basement and are covered by a pre-Sumian weathering crust; the acid metavolcanics lying at the base of the Lower Proterozoic section (2432 ± 22 Ma); and the comagmatic acid volcanics of the Nuorunen granites (2450 ± 72 Ma). The petrochemical characteristics of the Sumian–Sariolian basic metavolcanics of the Paanajarvi–Tsipringa structure show an affinity with volcanics of continental rifts. A persistent geochemically bimodal (andresite-basalt–dacite-rhyolite) association of volcanics can be traced, in our opinion, at different levels in the pre-Jatulian part of the section of the structure. Therefore, this association, in combination with clastogenic metasedimentary and sedimentary-volcanogenic units and tilloids, is regarded as a separate Sumian–Sariolian tectonic-facies complex with group rank. The geological, petrochemical, and geochronological data described in the paper testify that the Sumian–Sariolian sedimentary-volcanogenic rocks and the stratified basic and acid intrusives were formed in an active tectonic setting during an early stage in the development of a continental rift between 2.45 and 2.40 Ga as part of a single volcano-plutonic complex. The K-Ar method was used to date the last endogenic processes of the region as late- and post-Svecofennian.

Key words: *Isotope dating, Precambrian geology, correlation, volcanite geochemistry, and northern Kareliya.*

In northern Kareliya, Lower Proterozoic stratified complexes compose two structural zones with a long history of development: the sublatitudinal Paanajarvi–Tsipringa zone and the sublongitudinal Kuolajarvi zone. Both zones have natural extensions on the territory of Finland and stretch to the west and northwest as the Kuusamo and Salla–Jauratsi–Kittila structures, respectively (Fig. 1).

The Paanajarvi–Tsipringa syncline is composed of metamorphosed volcanologenic-sedimentary units of the Lower Proterozoic Karelian complex. The syncline contains rocks, which, according to the currently adopted stratigraphic scale, correspond to the Sumian, Sariolian, Jatulian, and (in the western part) Ludicovian superhorizons (*Stratigrafiya ...*, 1984; Voinov and Polekhovskii, 1985; Semikhatov *et al.*, 1991). Until recently, formations in Finland that are similar to the mentioned structures were referred to the upper Lapponian, 2.5 - 2.3 Ga old (Silvennoinen, 1985; Laajoki, 1986). Later, a few researchers suggested an older, Archean age (3.0 - 2.5 Ga) for a large part of the supracrustal complex (Gaal and Gorbatschev, 1987; Saverikko, 1987). These authors produced a scheme in which the Lapponian section correlates with the supracomplex of the Kuhmo–Suomussalmi greenstone belts in Finland and with the Lopian complex in Kareliya. However, the characteristics of rocks in the lower, middle, and upper Lapponian complexes of volcanogenic-sedimentary associations in northeastern Finland are extremely similar to the Sumian–Sariolan, Jatulian, and Ludicovian superhorizons, respectively (*Stratigrafiya ...*, 1984), of the Lower Proterozoic structural zone of northern Kareliya.

The majority of researchers who have studied these structures, which are quite common to the northern Fennoscandia, have taken their riftogenic nature for granted (Negrutsa, 1984; Saverikko, 1985; Silvennoinen, 1985; Gaal and Gorbatschev, 1987; Sokolov and Heiskanen, 1985; Laajoki *et al.*, 1989; Systra 1991; Huhma *et al.*, 1990; Pharaoh and Brewer, 1990). The characteristic features of these structures are the following: a close connection with deep faults, an association of clastogenic sediments and a contrasting volcanogenic series, numerous mafic-ultramafic layered intrusions (Kemi–Suhanko and Koillismaa–Narankovaara in northern Finland and the Olanga group in northern Kareliya), and swarms of mafic dykes.

The supracomplex of the Paanajarvi–Tsipringa structure (Fig. 2) was formed on the intensively eroded Archean basement, which is divided into blocks by deep faults and composed of plagiogranite gneisses and plagiomicrocline and microcline granites with numerous

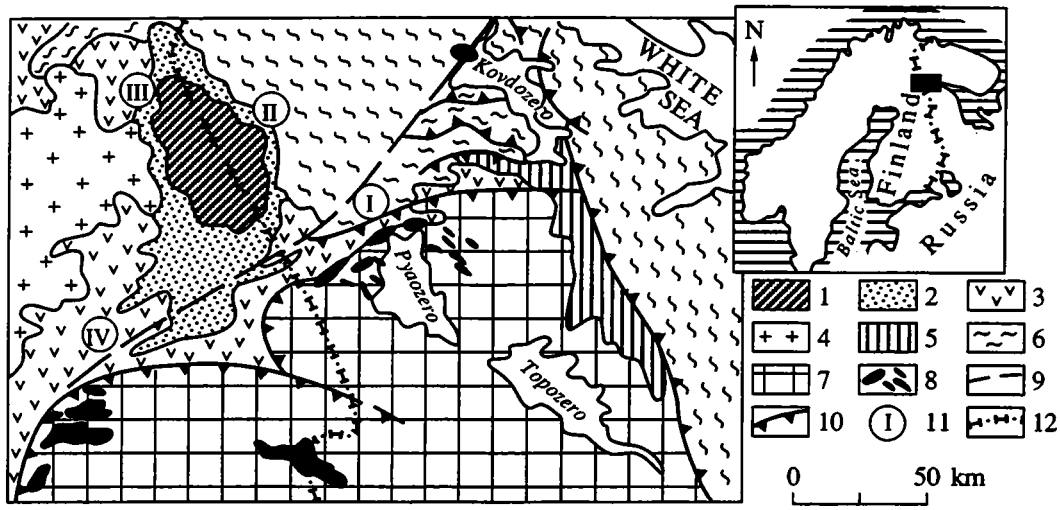

Fig. 1. A schematic geological map of northern Kareliya (including the territory of Finland, after Alapieti, 1982).
Early Proterozoic: 1 – Livvian–Ludicovian deposits, 2 – Jatulian deposits, 3 – Sumian–Sariolian (upper Lapponian) deposits, 4 – Svecofennian granitoids. Archean: 5 – Lopian complex, 6 – Belomorian complex, 7 – granite-gneisses and granitoids of the Saamian complex, 8 – layered intrusions and dykes, 9 – faults and strike-slip faults, 10 – overthrusts, 11 – structural zones of the Early Proterozoic: I – Paanajarvi–Tsipringa, II – Kuolajarvi, III – Salla–Jauratsi, IV – Kuusamo, 12 – state border between Russia and Finland.

relics of tonalites and amphibolites of the Tavajarvi complex. The plagiomicrocline and microcline granites intrude the plagiogranite gneisses and are the youngest formations of the basement complex. On the northern margin of the structure, the granitoids compose mapable bodies that, along with plagiogranite gneisses, a physical weathering crust, and poorly differentiated clastogenic sediments, are covered with plagio- and quartz–porphyrys and (closely related to them) basaltoids of the base of the Lower Proterozoic section (Heiskanen, 1980; *Stratigrafiya* ..., 1984; Polekhovskii, 1985; Korosov *et al.*, 1987; Zagorodnyi and Radchenko, 1988; Systra, 1990).

An association of basalt, andesite–basalt, and dacite–rhyolite composes the major part of the section of the pre-Jatulian Lower Proterozoic succession. Within the volcanologenic unit, there is a heterogeneous horizon of rudaceous rocks. In concrete sections in different parts of the structure, this horizon marks a definite stratigraphic level at which the acid volcanics that dominate below are substituted by mainly basic volcanics. Many researchers who have studied the geology of northern Kareliya have usually recognized this horizon as composed of polymictic conglomerate with pebbles of different granitoids, gabbros, basic volcanic rocks, and quartz porphyrys with blue opaline quartz (Negrutsa, 1984; Korosov *et al.*, 1987; Negrutsa, 1988; Systra, 1990). The composition of cement in the conglomerate is heterogeneous and varies from carbonate metasandstones and siltstones to tuffites, andesite–basalt tuffs, and inherent lava varieties with well-preserved intersertal, diabasic, and doleritic textures. The features characterizing these rudaceous formations are the following: the presence of fragments of acid volcanics; a lateral change in the composition of the dominant fraction of pebbles; extremely diverse classes of roundness, even in a homogeneous composition; poor sorting; and an exclusively puddinglike combination of the matrix with the debris, even in intensively schistosed varieties. These peculiarities indicate that some of the rocks of this stratigraphic level were formed in a setting of extremely dissected relief with intensive ice-rafting and coeval deposition of volcanogenic-sedimentary beds. The similarity of the subvolcanic quartz porphyrys and the rounded fragments with coarse parallel and cross lamination from the overlying basal stratum was considered by Systra (1990) to be an indication of intense vertical movements during the formation of conglomerates with scattered pebbles. Several geologists (Marmo and Ojakangas, 1984; Ojakangas, 1985, 1988) have noted the extensive development of dropstones in the Early Proterozoic structures of northeastern Finland; they consider these rocks to be typical of the Sariolian Superhorizon and believe that they formed in a geologic setting similar to that of the described units.

The stratigraphic subdivision of the lower Karelian complex has not yet been conclusively established. Some authors (Heiskanen, 1980; Polekhovskii, 1985) refer the acid volcanics to the Sumian Superhorizon, and all basalts and rudaceous metasediments are referred to a higher Sariolian level. Other researchers (Robonen, 1987) state that either the Sumian Superhorizon includes the entire complex of bimodal volcanics, or, on the contrary, the contrasting volcanogenic association with packets of rudaceous deposits composes the Sariolian Superhorizon (Zagorodnyi and Radchenko, 1988). The most probable variant is the one in which the Sumian and the Sariolian are regarded

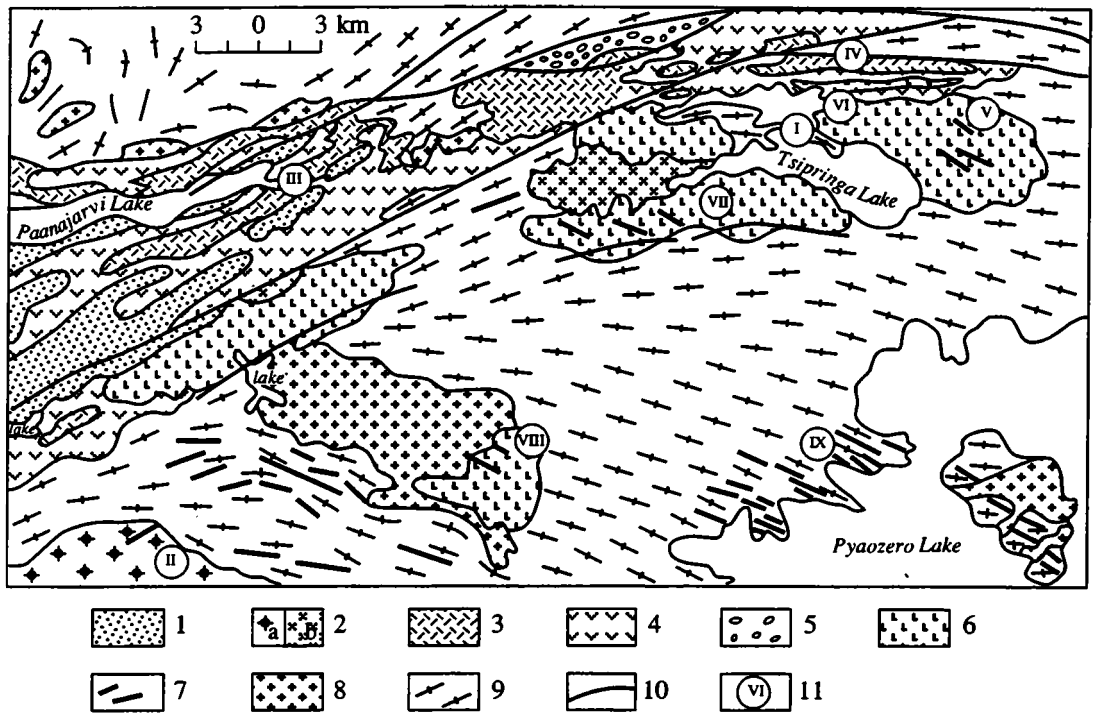

Fig. 2. Geological scheme of the Paanajarvi–Tsipringa structural zone.

1 – Jatulian Superhorizon. Sumian–Sariolian complex: 2: a – granites Nuorunen; b – monzodiorites, 3 – quartz-porphyry, 4 – basic metavolcanics, 5 – clastogene metasedimentary rocks, 6 – layered intrusions, 7 – mafic dykes. The rock complex of the basement: 8 – plagiomicrocline granite, 9 – plagiogranite-gneisse, 10 – faults, 11 – dated subdivisions: I – plagiomicrocline granite, U-Pb(Zr), 2710 ± 110 Ma; II – Nuorunen granites, U-Pb(Zr), 2450 ± 72 Ma; III – quartz porphyry of eastern Paanajarvi, U-Pb (Zr, early generation ?), 2522 Ma; IV - quartz porphyry of northern Tsipringa, U-Pb (Zr, early generation?), 2501 Ma, U-Pb(Zr), 2432 ± 22 Ma; V – Lukkulaisvaara massif, U-Pb(Zr), 2442 ± 1 Ma; VI – lava breccia cement of northern Tsipringa, U-Pb(Zr), 2436 ± 24 Ma; VII – Tsipringa massif, Sm-Nd, 2430 ± 26 Ma, U-Pb(Zr), 2441 ± 1 Ma; VIII – Kivakka massif Sm-Nd, 2420 ± 23 Ma, U-Pb(Zr) 2444 ± 1 Ma; IX – gabbro-norite dyke swarm, Sm-Nd, 2470 ± 65 Ma.

as part of a unified tectonic-facies complex of the early riftogenic stage of formation of the structural zone (Salop, 1982; Negrutsa, 1984; Laajoki, 1988; Laajoki *et al.*, 1989; Manninen, 1991). Field research and an analysis of the literature on the geology and stratigraphy of the region have brought us to the conclusion that there are two levels of acid volcanics within the Sumian–Sariolian complex (Fig. 3). The acid volcanics of the lower level are mainly composed of extrusive facies of "magnophyric quartz-," quartz-, and plagioporphyrys in association with subvolcanic bodies that are similar in composition but somewhat more coarse-grained. This part of the section outcrops in the eastern area of the Paanajarvi structure. In a few cases, the dacite–rhyolite rocks overlie or are laterally substituted by less massive basalt and andesite–basalt flows (Korosov *et al.*, 1987).

At a higher level, a heterogeneous "transition" member occurs with tillitelike rudaceous rocks and polymictic conglomerates including varieties with volcanogenic cement. Locally, as the quantity of pebbles gradually decreases, these kinds of rocks in the series of outcrops grade into pillow basalts and andesite–basalts. Above the "transition" member, the section shows a sudden increase in the share of basaltoids with well-preserved volcanogenic textures and structures; distinctly fluidal tuffolavas and banded tuffs dominate among the acid volcanics. Also present are characteristic horizons of tuffolavas with large rounded fragments of massive subvolcanic quartz porphyry cemented by fluidal fine-grained rocks of a similar composition. Members of acid and basic rocks alternate in the section, while andesite basalts generally prevail. This level of volcanics is usually observed in outcrops to the north and west of Tsipringa Lake. The thickness of the volcanics of both levels and of the rudaceous rocks of the "transition" member vary noticeably; locally, individual members are completely wedged out, probably owing either to the character of volcanic activity (sudden facies replacements) or to the varying erosion of the supracomplex as a result of undulation of the major axis of the fold structure (Polekhovskii and Voinov, 1987).

The metavolcanics of the Sumian–Sariolian complex form a distinct bimodal basalt–rhyolite association of the calc–alkaline and subalkaline series (Fig. 4; Table 1). On *AFM* diagrams and diagrams of the sums

of alkalies–silica, the compositions of the basic and acid volcanics form compact fields with a distinct gap in the area of andesites and andesites–dacites. The petrogenetic diagram MgO versus $FeO–Al_2O_3$ (Pearce *et al.*, 1977) shows that most of the compositions of the basic volcanics are located in the field corresponding to the basalts of continental rifts (Fig. 5). The partly tholeiitic and predominantly calc–alkaline nature of the basaltoids is shown by the *AFM* Ti–Zr–Sr diagrams (Fig. 6) (Pearce and Cann, 1973; Pearce, 1982). The rather preliminary petrogeochemical studies performed recently do not reveal significant and regular differences in the composition of volcanics from the lower and upper levels. The results of the studies, however, allow us to relate the entire bimodal volcanogenic complex to continental rifting. Therefore, we consider it possible to incorporate the pre-Jatulian stratified beds of the Paanajarvi–Tsipringa structure into the Sumian–Sariolian riftogenic complex in the rank of a group; this is based on evidence that the rather similar compositions of the contrasting volcanics of both levels form a stable paragenetic association, and that the unit dividing them has manifestations of tillites and can be correlated, owing to its volcanogenic peculiarities, with the classical Sariolian in central Kareliya (Eliseev *et al.*, 1982) and in northeastern Finland (Ojakangas, 1985, 1988).

The layered intrusions of the Olanga group are spatially and genetically associated with the sedimentary-volcanogenic formations of the Sumian–Sariolian (Turchenko *et al.*, 1991). The Kivakka, Lukkulaisvaara, and Tsipringa massifs are the largest; they have different geologic relations with the Lower Proterozoic beds. The uppermost portion of the layered Lukkulaisvaara intrusion are covered in the northern part of the area by lava breccia and by tuff and lava conglomerates with pebbles of quartz porphyry and fragments of the underlying gabbro. The lava conglomerates distinctly truncate the banding caused by magmatic layering. There

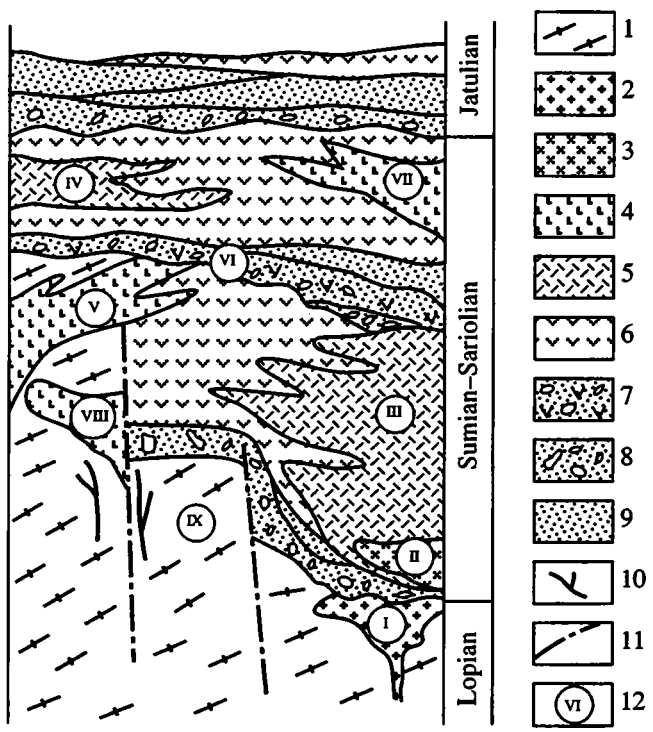

Fig. 3. Lithostratigraphic scheme of the section of the Sumian–Sariolian volcano-plutonic complex of the Paanajarvi–Tsipringa structure.

1 – plagiogranite–gneisses of the pre-Karelian basement, 2 – porphyry plagiomicrocline granite, 3 – Nuorunen subalkaline granite, 4 – a group of layered intrusions, 5 – quartz porphyry, plagioporphyry, 6 – basic metavolcanics, 7 – conglomerate and breccia with volcanogenic cement, 8 – rudaceous formations with terrigenous cement, 9 – metasandstones of diverse composition, 10 – mafic-ultramafic dyke swarms, 11 – faults, 12 – dated lithostratigraphical subdivisions.

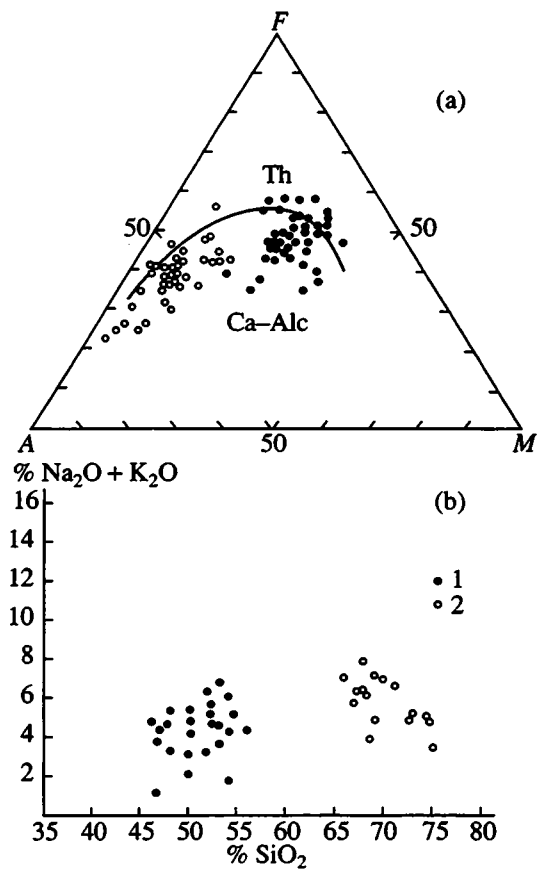

Fig. 4. (a) The *AFM* diagram of metavolcanics of the Sumian–Sariolian complex in the Paanajarvi–Tsipringa structure showing their calc–alkaline composition. Dividing line after Irvin–Baragar. Th – tholeiitic series, Ca–Alc – calc–alkaline series. (b) Diagram of $Na_2O + K_2O$ versus SiO_2 for the same rocks showing the bimodal character of metavolcanics.

1 – metabasalt, 2 – metafelsite.

Table 1. Chemical composition of volcanogenic and intrusive rocks of the Sumian-Sariolian igneous-plutonic complex

Number of sample / Chemical composition	227 ST-86	227-1 ST-86	229 ST-86	3-6 BA-86	20-1 BA-86	21-3 BA-86	22-0 BA-87	32-1 BA-86	62 ST-87	21 ST-87	1-17 ST-87	63 ST-87	40-11 BA-87
	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	52.50	52.23	53.83	53.57	53.14	50.39	51.25	52.42	52.75	50.85	54.95	49.95	55.32
TiO_2	0.54	0.62	0.65	0.60	0.70	0.65	0.67	0.77	0.71	0.64	0.64	0.63	0.64
Al_2O_3	13.15	13.92	14.69	14.35	14.75	15.75	14.72	13.13	12.30	14.00	14.25	13.85	13.68
Fe_2O_3	8.03	10.60	10.88	10.05	10.69	12.02	9.54	12.39	1.30	1.30	1.52	1.74	10.46
FeO	5.28	7.47	6.81	6.30	6.61	6.62	5.17	8.66	8.56	8.45	7.28	6.89	7.35
MnO	0.22	0.16	0.25	0.25	0.29	0.17	0.21	0.29	0.19	0.15	0.15	0.12	0.20
MgO	8.46	8.66	6.48	5.35	5.82	6.96	4.64	7.89	8.34	7.67	6.67	5.33	5.55
CaO	8.86	5.63	6.22	7.26	7.75	6.22	9.14	7.02	7.91	9.33	7.58	11.09	7.67
Na_2O	4.38	3.75	3.34	5.74	4.42	2.98	4.58	4.49	2.95	2.81	2.90	3.67	3.70
K_2O	0.89	2.70	2.16	0.10	0.43	1.92	0.72	0.18	0.98	0.43	1.45	0.77	0.60
P_2O_5	0.12	0.18	0.04	0.04	0.08	0.08	0.05	0.07	0.07	0.07	0.09	0.08	0.04
Ignition losses	2.36	1.05	0.97	2.23	1.43	2.36	3.98	0.85	3.25	4.48	2.07	4.85	1.64
Total	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.31	100.18	99.55	98.97	99.50
Rb	17	66	52	4	4	34	4	1	3	13	44	23	24
Sr	216	181	212	248	295	172	323	181	102	157	164	162	327
Ba	296	983	850	140	232	880	140	29	50	28	495	281	181
Y	13	15	19	18	18	15	17	17	18	16	16	16	17
Zr	86	101	96	77	95	83	89	68	60	55	85	78	79
Ti	3720	3896	3900	3600	4808	4308	4307	4020	4676	5096	4476	4112	4921
Nb	6	7	2	2	4	3	3	3	2	3	4	4	5

Table 1. (Contd.)

Number of sample / Chemical composition	31-1 BA-87	40 BA-87	46 BA-87	62-2-1 BA-87	63 BA-87	40-1-Å BA-87	40-6 BA-87	40-7 BA-87	62-2-3 BA-87	61 ST-87	3-11 BA-86	28 BA-87	35-1 BA-87
	14	15	16	17	18	19	20	21	22	23	24	25	26
SiO_2	52.18	57.89	53.05	57.34	54.36	47.00	54.36	52.45	52.64	56.15	53.88	69.15	75.30
TiO_2	0.86	0.59	0.64	0.69	0.64	1.10	0.63	0.78	0.66	0.78	1.15	0.92	0.41
Al_2O_3	14.61	12.86	15.24	15.30	13.32	16.37	14.29	13.90	15.18	14.25	20.18	12.14	8.83
Fe_2O_3	11.53	9.07	9.67	7.86	10.93	12.80	11.54	12.66	12.19	1.53	2.30	8.07	4.19
FeO	8.18	6.90	4.94	5.31	7.00	8.83	8.06	8.60	7.40	7.54	6.26	5.22	2.64
MnO	0.19	0.26	0.16	0.14	0.20	0.32	0.18	0.23	0.18	0.16	0.12	0.03	0.08
MgO	7.08	6.53	6.49	5.02	6.97	7.74	6.28	7.08	5.73	6.51	4.78	2.33	0.52
CaO	6.00	7.40	7.16	3.85	7.54	7.85	5.82	7.54	7.12	5.81	1.82	0.74	3.19
Na_2O	4.43	4.06	3.56	6.80	2.45	3.19	2.33	0.97	2.45	3.48	5.22	3.85	2.43
K_2O	0.10	0.35	0.61	0.41	2.09	0.49	1.87	0.61	0.47	0.89	0.90	1.43	1.67
P_2O_5	0.04	0.04	0.04	0.04	0.06	0.05	0.04	0.06	0.04	0.11	0.23	0.19	0.04
Ignition losses	2.48	0.45	2.88	2.05	0.95	2.60	2.16	3.21	2.84	2.72	2.76	0.85	3.13
Total	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.93	99.50	99.50	99.50
Rb	3	3	13	8	55	14	45	19	11	28	22	36	73
Sr	138	101	324	71	117	191	78	188	334	176	32	19	46
Ba	50	110	250	140	399	380	580	280	160	455	246	160	260
Y	19	16	17	9	15	21	15	16	17	18	13	52	43
Zr	86	79	101	83	79	117	82	94	91	86	242	294	280
Ti	5160	3540	3840	4140	4612	6600	3780	4880	3960	5375	6602	5520	2460
Nb	8	7	6	8	3	12	7	7	7	3	11	14	14

Table 1. (Contd.)

Number of sample / Chemical composition	36 BA-87	38 BA-87	39-2 BA-87	39-4 BA-87	512 EK-87	518 EK-87	519 EK-87	514 EK-87	514-1 EK-87	80 BA-88	27 BA-87	10-1 BA-86	7-3 BA-86	7-1 BA-86
	27	28	29	30	31	32	33	34	35	36	37	38	39	40
SiO_2	68.83	75.88	72.33	73.85	69.62	78.35	70.28	70.96	70.82	70.13	69.29	69.27	67.60	72.60
TiO_2	0.88	0.63	0.62	0.58	0.91	0.42	0.65	0.55	0.64	0.81	0.80	0.94	0.73	0.79
Al_2O_3	12.83	13.28	10.24	11.95	12.94	9.71	12.93	12.46	12.28	12.27	12.45	12.18	11.32	10.31
Fe_2O_3	5.97	2.79	3.62	2.83	5.27	3.57	6.04	4.84	6.06	5.82	6.73	6.25	4.34	5.91
FeO	3.30	0.93	1.79	1.38	3.01	1.97	3.62	2.85	3.97	3.72	3.99	4.03	2.42	3.47
MnO	0.10	0.30	0.06	0.04	0.05	0.05	0.02	0.05	0.09	0.08	0.03	0.06	0.07	0.08
MgO	0.51	0.10	0.29	0.22	0.45	0.52	0.73	0.38	0.45	0.68	2.63	1.26	4.31	2.15
CaO	1.84	0.57	4.41	2.21	1.16	1.27	0.65	2.06	1.01	1.62	0.58	1.98	2.96	1.24
Na_2O	3.82	2.94	0.75	1.63	2.67	1.20	4.00	1.25	3.64	3.95	2.54	2.13	3.42	1.76
K_2O	3.88	2.66	2.75	3.99	5.82	2.91	3.68	4.92	3.92	3.34	3.43	2.97	3.31	3.84
P_2O_5	0.18	0.10	0.12	0.10	0.17	0.04	0.06	0.07	0.09	0.17	0.18	0.41	0.18	0.18
Ignition losses	0.65	0.25	4.31	2.10	0.25	1.45	0.25	1.97	0.54	0.25	0.84	2.01	1.28	0.66
Total	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50	99.50
Rb	98	82	86	101	106	116	71	145	59	90	98	69	61	94
Sr	145	28	30	51	67	34	58	40	162	129	11	33	273	175
Ba	1183	940	400	1300	1800	770	1490	1950	880	1150	680	1780	706	980
Y	48	38	58	50	52	36	50	77	60	37	28	17	35	42
Zr	368	401	351	400	377	273	534	478	517	356	221	377	521	556
Ti	4971	3780	3720	3480	5241	2520	3900	3300	3840	4860	4469	5640	4539	4740
Nb	19	20	20	18	19	15	27	24	23	18	12	17	22	23

Table 1. (Contd.)

Number of sample / Chemical composition	3-14 BA-86	224 ST-86	233 ST-86	226 ST-86	222-1 ST-86	222 ST-86	8-1 BA-86	13-1 ST-87	15-2 ST-87	25-1 BA-86	51 ST-87	53 ST-87	18 ST-87	S-3333
	41	42	43	44	45	46	47	48	49	50	51	52	53	54
SiO_2	69.51	68.83	74.89	74.25	66.99	66.60	67.22	77.90	73.40	72.94	69.90	71.70	65.60	74.92
TiO_2	0.95	0.63	0.59	0.99	0.95	1.13	0.88	0.58	0.57	0.95	0.64	0.65	0.84	0.25
Al_2O_3	12.37	10.62	12.28	17.53	12.62	11.80	13.92	11.80	11.50	11.60	12.00	12.70	15.80	11.23
Fe_2O_3	6.12	3.05	3.82	4.11	8.00	9.52	5.30	1.77	1.47	5.35	1.71	1.86	2.81	0.24
FeO	4.13	0.98	1.91	2.41	4.67	6.44	3.52	1.19	0.66	3.04	2.64	2.77	1.58	1.94
MnO	0.10	0.07	0.03	0.04	0.10	0.13	0.10	0.02	0.02	0.04	0.03	0.05	0.05	0.02
MgO	1.02	0.55	0.80	1.64	1.75	1.17	1.34	0.70	0.85	1.47	0.54	0.70	1.19	0.44
CaO	1.62	5.95	0.39	1.90	1.18	2.45	1.72	0.33	2.80	0.55	2.64	1.32	1.87	0.63
Na_2O	3.35	1.32	1.88	3.05	1.96	3.23	3.93	0.17	3.76	2.18	1.45	1.50	1.05	3.16
K_2O	3.81	3.04	3.17	2.29	4.70	2.76	4.08	3.45	3.00	3.41	4.00	4.32	5.12	5.52
P_2O_5	0.21	0.09	0.12	0.24	0.26	0.25	0.20	0.15	0.15	0.27	0.16	0.16	0.16	0.02
Ignition losses	0.44	5.37	1.52	0.50	0.98	0.50	1.19	1.78	3.20	0.70	3.51	2.14	3.30	0.80
Total	99.50	99.50	99.50	99.50	99.50	99.50	99.60	99.82	100.38	99.50	99.22	99.87	99.37	99.17
Rb	85	76	103	41	95	66	99	99	60	108	112	126	179	170
Sr	158	59	30	132	145	170	157	24	45	16	26	11	18	92
Ba	930	1560	1014	1147	1870	540	1299	916	845	814	1146	1162	1536	950
Y	46	67	28	28	39	32	25	32	40	15	41	44	80	39
Zr	397	517	346	399	430	268	411	375	385	392	380	415	683	295
Ti	5700	3780	4004	6174	5700	6880	5590	3669	3139	6093	3622	4034	4616	1481
Nb	17	22	16	18	16	11	16	19	19	15	19	20	19	18

Notes: I. Analyses 1 - 8, 13 - 22, and 25 - 46 were carried out at the VIMS laboratory; FeO content and ignition losses were determined chemically; the rest of the elements were analyzed quantum-metrically. FeO is excluded from the total sum, whereas Fe_2O_3 is included as the total quantity of iron.
II. Analyses 9 - 12, 23 - 24, and 47 - 54 were carried out at the PGO "Arkhangel'skgeologiya" using the chemical method.
III. Samples 1 - 24 are metabasalts and meta-andesite-basalts; 25 - 53 are metadacites and metarhyolites; 54 is granite of the Nuorunen massif. The contents of the major elements are given in %, and those of rare elements, in g/t.

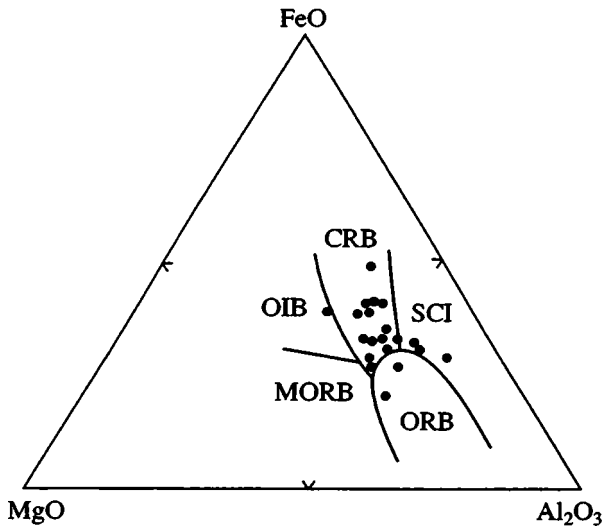

Fig. 5. A diagram of MgO versus FeO–Al_2O_3 for basic metavolcanics of the Sumian–Sariolian complex in the Paanajarvi–Tsipringa structure (after Pearce and Cann, 1977). (OIB) oceanic island basalts, (MORB) mid-oceanic ridge basalts, (CRB) continental rift basalts, (ORB) island arc basalts, (SCI) basalts of the spreading center islands.

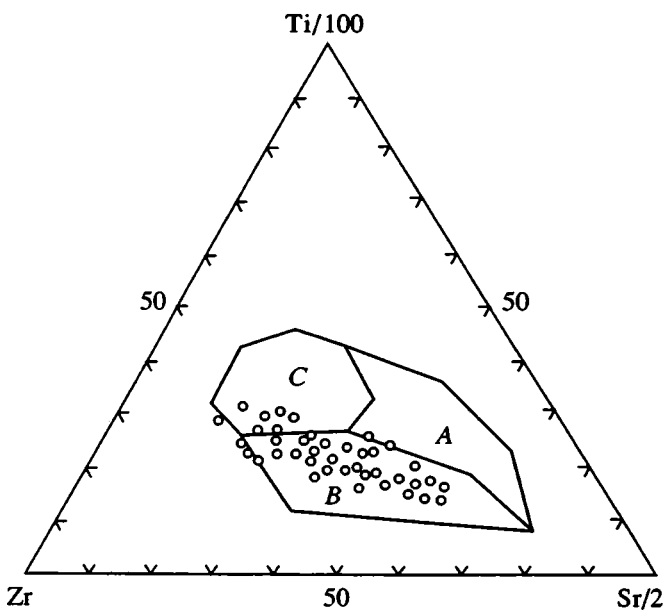

Fig. 6. A Zr–Ti/100–Sr/2 diagram for basic volcanics of the Sumian–Sarolian complex Paanajarvi–Tsipringa structure (Pearce, 1982). *A* – low-alkaline toliites, *B* – calc–alkaline basalts, *C* – toliitic basalts.

are also occurrences of individual bodies of gabbroids of the Tsipringa intrusion that either cut through the volcanics of the upper level or form sills among the metabasalts in several localities. These data allow us to use the mafic intrusions of the Olanga group as geologic–geochronologic markers to determine the age of the Lower Proterozoic stratified rocks. The latter, in turn, can be considered in combination with the basic intrusions and mafic dykes as a single riftogenic volcanic-plutonic association (Fig. 3), which was formed during the pre-Jatulian stage of crustal tension in the Karelian craton (Felitzin *et al.*, 1989). The metamorphic alteration in volcanogenic-sedimentary deposits of the region is concurrent with the greenschist facies (chlorite–sericite and biotite–chlorite subfacies). Two stages of metamorphism can be identified. The first stage is primarily associated with autometamorphic processes and did not influence the structural process. During the second, post-Jatulian stage, the stratified members and layered intrusions experienced foliation and were regionally metamorphosed under greenschist facies conditions (Polekhovskii and Voinov, 1987). Only the marginal zones of the intrusive bodies show intense metamorphism and foliation. The original volcanogenic structures and textures remained almost intact in the central parts of thick lava flows. Moreover, the sedimentary-volcanogenic rocks have narrow linear zones of superimposed schistosity, which correspond to the latest deformations near the faults (Systra, 1991).

Information recently obtained on Sm-Nd dating of layered intrusions and dykes (Amelin and Semenov, 1990) and, in particular, U-Pb isochronous zircon datings (Semenov *et al.*, in press) have shown that their formation took place during a very short time period. For example, the time of formation of the Kivakka massif is estimated as 2444 ± 1 Ma (U-Pb isochrone, Zr) and 2420 ± 23 Ma (Sm-Nd, whole-rock samples), and the age of the olivine gabbro–norite dykes located in the Archean granite–gneiss basement corresponds to 2470 ± 65 Ma (Sm-Nd, whole-rock samples). The Lukkulaisvaara massif, unconformably overlain by an upper volcanite member, is 2442 ± 1 Ma old (U-Pb isochrone, Zr), whereas the age of the gabbroids of the Tsipringa massif intruding that volcanogenic member was established at 2441 ± 1 Ma (U-Pb, Zr) and 2430 ± 26 Ma (Sm-Nd, whole-rock samples). These geochronological data allow us to determine the age of the upper horizon of volcanics that are clamped between basic intrusions in a kind of "geologic bracket." If the geologic observations on relationships between the intrusions and the volcanics prove to be true, then an interval of about 5 Ma should cover a number of events associated with the formation of the Lukkulaisvaara massif, its deformation and unroofing, the erosion of the upper layered horizons, and the accumulation of sedimentary-volcanogenic beds that were thick enough for the crystallization of the Tsipringa intrusion gabbroids, which intrude these beds. Under the conditions of the developing continental rift, the abundance of geologic events and the evolutionary rate of processes seem to be reasonably conceivable (Wilson, 1989). Similar layered intrusions of the Koilismaa complex in northern Finland are 2436 ± 5 Ma old (U-Pb method on zircons), and the

Penikat intrusion dated by the Sm-Nd method on whole-rock samples is 2410 ± 64 Ma old (Huhma *et al.*, 1990).

The differences in the age determinations of the pre-Jatulian part of the supracrustal complex have revealed the practical importance of dating both the quartz porphyrys and their most likely intrusive comagmatic rocks (granites of the Nuorunen massif), which are part of a bimodal volcanic-plutonic association that formed at an early riftogenic stage in the structural zone development.

In this respect, the combination of the studied rocks is considered to be not only the Sumian–Sariolian parastratotype (Levchenkov *et al.*, 1990), but also a tectonic-facies complex. This complex can be correlated with the stratotype formations of the Lehta structure (Levchenkov *et al.*, 1994) and the lower Lapponian members of Lapland in Finland (Manninen, 1991) by the formational characteristics of the rocks and, primarily, by the common features in the geodynamic settings of their formation. It is necessary to note that the datings given below for the acid volcanics and granitoids of the Paanajarvi–Tsipringa structure precede the undoubtedly more precise datings of the Olanga layered intrusions (2442 - 2441 ± 1 Ma; Semenov *et al.*, in press) as well as those of the granite of the Kormanka massif and the Lehta metarhyolite (2449.3 ± 3.7 and 2442.8 ± 4.8 Ma, respectively; Levchenkov *et al.*, 1994). Nonetheless, the obtained datings of related complexes or of those controlled by their geologic relations are very similar, which provides evidence in favor of our geological interpretation.

The geochronological studies of the processes of formation of the Paanajarvi–Tsipringa structure were carried out using a complex of isotope methods. In order to date the igneous member, we selected the least altered and foliated varieties of quartz porphyrys from the northern shore of Tsipringa Lake (samples 13-1ST, 15-2ST, and 53-2ST, upper level) and from the eastern shore of Paanajarvi Lake (Sample BA-36, lower level) and the cement of lava breccia from the intermediate member. A granite sample from the Nuorunen massif was also analyzed. Metamorphosed basalt and quartz porphyry were studied by the K-Ar method on amphibole, muscovite, and plagioclase to fix the termination of endogenic thermal events.

Two zircon varieties in different proportions were found in the samples of acid volcanics and lava breccia cement (samples 3-11BA, 13-1ST, 15-2ST, 53-2ST, BA-1, and BA-36). One of the two varieties was represented by an early generation of grains; the shapes varied from oval to prismatic, and the colors ranged from yellowish to brown. The surfaces of some of the grains show traces of dissolution. The inner part of many crystals is heterogeneous and semitransparent with varying metamictization grades, occasionally with thin zonation and dustlike inclusions. Individual grains have thin and more transparent coatings of zircon of a later generation.

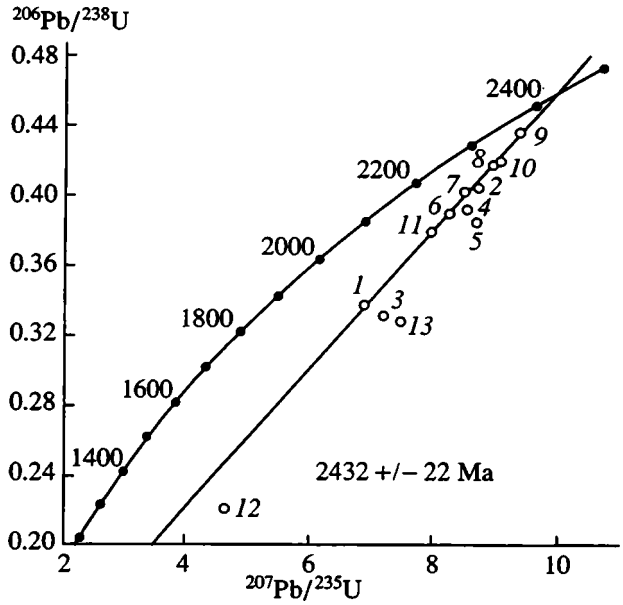

Fig. 7. Concordia plot for zircons from quartz porphyrys on the northern shore of Tsipringa Lake. In this plot and in Figs. 8 and 9, the numbers of dots correspond to the numbers of the analyzed fractions of zircons in Table 2.

The grains of the other zircon variety are colorless or white euhedral prisms with zonation and numerous gas–liquid inclusions. The zircon of this generation dominates in the studied samples. The brown grains of the early-generation zircon in samples 13-1ST and BA-36 show high contents of uranium and a low Th/U ratio, judging from the results of $^{208}Pb/^{206}Pb$ measurements, and the oldest age values according to $^{207}Pb/^{206}Pb$ ratios: 2501 and 2522 Ma, respectively (Table 2). The concordia plot shows that the figurative points of these two samples (Fig. 7) are situated to the right of the other figurative points. The white and transparent grains of the later zircon variety in Sample 13-1ST in combination with four fractions of other zircon samples [including a sample from lava breccia volcanogenic cement (Sample 3-11BA)], which lack the early variety of the mineral, form a discordia that defines their isotope age at $2432 \pm {}^{24}_{20}$ Ma (MSWD = 4.2; n = 6, model 2). It should be noted that recently obtained data (oral communication by O.A. Levchenkov) indicate that the same discordia fits the points corresponding to the colorless prismatic zircons of the quartz porphyry pebbles; they form the clastic part of lava conglomerates, truncating the layering of the Lukkulaisvaara massif. The position of the five figurative points on the plot is between the discordia and the points of the brown zircons; this probably implies the presence of a certain amount of early-generation zircon in the samples. The geochemical peculiarities of the U-Pb system in the brown zircons imply that this relict zircon belongs to the Archean crustal rocks.

The Nuorunen granite massif. The datings were conducted for fractions of zircon sample S-3333

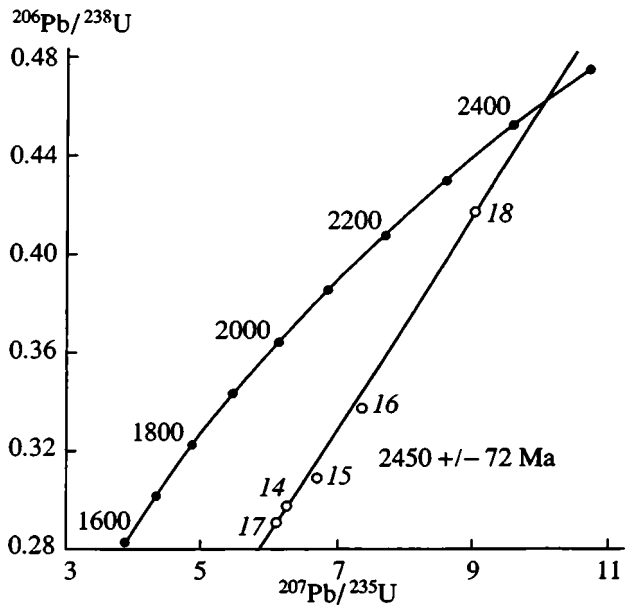

Fig. 8. Concordia plot for zircons from Nuorunen granite massif.

(kindly provided by Yu.I. Systra) obtained by dimensional fractionation, abrasive processing, and density grading in Clerici solution. The sample has two varieties of zircon. One of them contains euhedral, subeuhedral, and dark brown grains of zircon habit. A few crystals have nuclei. The other variety is composed of euhedral and subeuhedral transparent and opaque grains of zircon habit. The grains may have gas–liquid inclusions and sometimes fine zonality.

The content of uranium in the zircon and the Th/U ratio are analogous to those in zircons from acid volcanics, which probably evidences the genetic relations between the granite melt and the rhyolite magma (Table 2). In the concordia plot, the discordia is traced by five figurative points giving the following datings: $2458 \pm {}^{99}_{68}$ Ma for the upper intersection and $209 \pm {}^{384}_{582}$ Ma for the lower intersection (MSWD = 57, model 2) (Fig. 8). The high MSWD value reflects the isotopic heterogeneity of zircon in Sample S-3333, which is also indicated by lower uranium contents (72.7 and 80.8 μg/g) in zircon fractions + 100 μm after abrasion processing.

The elimination of these two fractions from the isochrone plot sharply reduces the MSWD value to 3 without considerable changes in the age value: $2450 \pm {}^{82}_{61}$ Ma and $254 \pm {}^{322}_{344}$ Ma. The position of figurative points *15* and *16* to the right of the discordia can be attributed to the presence of relict zircons with a lower uranium content in the central parts of the grains of these fractions. The data indicate the coeval formation of the Nuorunen granite massif and the quartz porphyrys.

The final stage of the Archean history of development of the region was dated by zircon from Sample ST 201-3 of microcline granites that intrude the plagiogranite gneisse of the basement in the central part of the structure. Zircon is represented by three varieties of grains of euhedral and subeuhedral aspect, either of zircon or, less frequently, of hyacinth habit; the crystals have cavernous surfaces and thin casings of fresh zircon material with a lower double refraction. The varieties differ in color and grain size.

The results of studies on zircon fractions with various grain sizes are shown in Table 2. One of the fractions was abrasively processed. Zircon is characterized by high uranium and common lead contents. The removal of casings from the zircon grains somewhat increases the isotope age (fraction no. *21*, Table 2). This indicates that the casings appeared during one of the postcrystallization stages of this granite. The isochrone plot (Fig. 9) shows the isotope age of the zircon to be $2702 \pm {}^{96}_{72}$ Ma (MSWD = 7, model 2).

Isotope studies of the K-Ar system of minerals that formed as a result of metamorphic influence allowed us to determine the time of metamorphism. The most effective way to do this is to study at least two cogenetic minerals. For this study, we chose metamorphic minerals from two samples of metabasalt and metarhyolite, which were collected in close stratigraphic proximity from the section on the northern shore of Tsipringa Lake.

Sample 63-ST is a metabasalt collected from the upper volcanic level of the Sumian–Sariolian complex. The mineral composition of the metabasalt is Pl + Amph (by Px) + Bt ± Ep. The rock is barely foliated and contains relicts of the oiginal magmatic structure. We analyzed the systems of two amphiboles and one biotite. Though the amphiboles have different chemical compositions (the potassium content in Amph-2 is almost twice as large as that in Amph-1), both minerals are of the same K-Ar age (Table 3). Taking into account the available petrological and structural data (Polekhovskii and Voinov, 1987), we can suppose that Amph-1 was formed through the replacement of magmatic pyroxene during the stage of autometamorphic alteration in the volcanogenic member, while Amph-2, with higher potassium content, could have evolved coevally with biotite during the process of post-Jatulian regional metamorphism, which reset the isotopic K-Ar system of the early amphibole about 1700 Ma ago. An even later thermal process (about 1500 Ma ago) was determined by K-Ar datings on biotite from the same metabasalt sample and muscovite from the quartz porphyry (Sample 15-2-ST, Table 3) from the upper level of acid volcanics. The mineral composition of metarhyolite is Qu + Ab + Mu ± Mi ± Ep ± Ap. The rock is intensively foliated, and muscovite is the principal structure-forming mineral and is mainly concentrated in the youngest linear zones of foliation. The biotite, in contrast to the muscovite, corresponds to an earlier structural plan in the metabasalt sample but has the

Table 2. Lead and uranium isotopes in zircons from the rocks of the Paanajarvi–Tsipringa structure

Nos.	No. of sample, fraction	Weight, mg	Content, ppm		Measured isotope ratios			Calculated isotope ratios		Age
			U	Pb	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
	Cement of lava breccia									
1	3-11 BA, opaque	2.13	111	44.1	1590	6.3987	4.5334	0.33749	6.9074	2328
	Quartz porphyry									
2	13-1 ST, gross	3.28	105	50.9	1660	6.0960	4.5019	0.40488	8.7418	2419
3	+45, L	4.30	798	32.0	1058	5.9022	4.3726	0.33182	7.2144	2431
4	+45, H	3.41	53.7	25.3	1023	5.8632	4.3147	0.39190	8.5618	2439
5	Brown	0.53	566	246	3210	5.9498	6.7480	0.38475	8.7191	2501
6	White	6.16	91.2	42.3	3165	6.3259	4.5232	0.38991	8.2919	2393
7	Transparent	1.67	90.1	43.3	2180	6.2615	4.2380	0.40176	8.5358	2392
8	15-2 ST, gross	2.37	101	50.5	1340	6.0549	4.1803	0.41774	8.9813	2412
9	+45, ap 60	3.19	109	56.2	2760	6.2530	4.5627	0.43653	9.3608	2408
10	+45, ap 30	4.43	123	63.9	980	5.9046	3.9199	0.41943	9.0583	2420
11	53-2 ST, gross	4.50	102	45.6	4490	6.4289	4.6353	0.37933	7.9972	2379
12	BA-1, light, transparent	2.28	63.6	17.8	793	5.9193	2.9319	0.22041	4.6569	2382
13	BA-36, brown	0.66	781	283	1608	5.7472	9.5880	0.32803	7.5260	2522
	Granite, Nuorunen massif									
14	S-3333 + 100	3.78	182	75.2	262.5	4.9633	2.9807	0.29706	6.2796	2383
15	+100; ap 50	8.02	72.7	26.8	1990	6.0878	4.4239	0.30814	6.7174	2436
16	+100; ap 50	3.96	80.8	32.9	943	5.7992	4.1463	0.33599	7.3807	2448
17	100; ap 50	2.10	179	62.5	900	5.9683	4.0653	0.28982	6.1418	2388
18	H	0.96	116	64.2	364.4	5.1899	3.3276	0.41587	9.0767	2438
	Microcline granite, a vein in Archean basement									
19	201-3 ST 45-10L	2.10	1140	445	272.9	4.5423	4.5927	0.29958	7.2454	2610
20	+100	2.95	1032	408	285.7	4.5797	4.7082	0.30559	7.4001	2612
21	45-100; ap 25	2.24	1146	586	237.0	4.3166	4.0816	0.47844	9.4131	2656
22	+50	1.08	10.80	450	322.2	4.6797	5.0214	0.32961	7.9918	2614

Notes: Size of fractions in μm; ap – abrasion processing, number on the right is the proportion of extracted zircon; L – light fraction, H – heavy fraction. The constants used are the following: $\lambda_{238} = 0.155125 \times 10^{-9}$ years^{-1}; $\lambda_{235} = 0.9848507 \times 10^{-9}$ years^{-1} $^{238}U/^{235}U = 137.88$. Pb isotopic composition used in calculations according to Stacey-Kramers model (Stacey and Kramers, 1975). Ambiguity of measurement of isotope relations $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ does not exceed 1.5%.

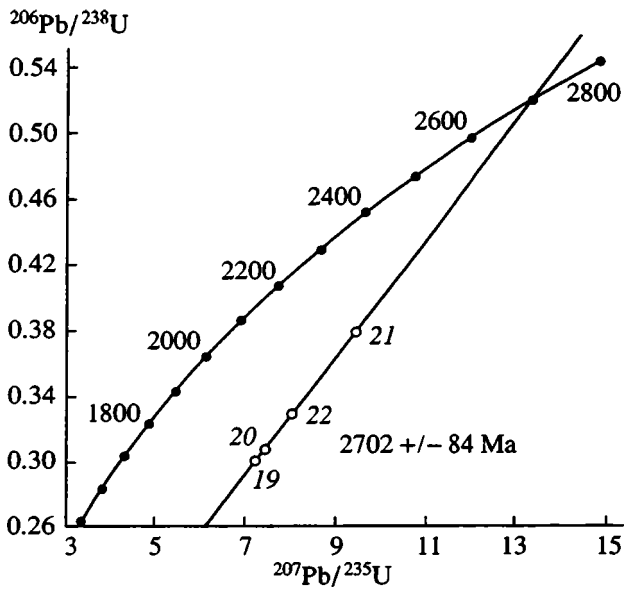

Fig. 9. Concordia plot for zircons from the microcline granites of the Archean basement.

same K-Ar age, apparently due to the disturbance of the K-Ar isotope system. The K-Ar studies of rocks, therefore, determine the time of the greenschist metamorphism at 1680 - 1700 Ma ago and the time of the later process, which caused foliation of acid volcanics, the formation of muscovite, and disturbance of the K-Ar system of an earlier biotite in metabasalts, at 1500 Ma.

The results of geochronological research described above assist in reconstructing the sequence of geologic events in the formation of the Paanajarvi–Tsipringa structure.

The Archean history of evolution of the northern part of the Karelian craton was completed by the formation of plagiomicrocline granites 2.7 Ga ago; these rocks were later covered by Lower Proterozoic basalt flows. The accumulation of the Sumian–Sariolian volcanogenic-sedimentary complex and the formation of associated and comagmatic intrusives occurred in an active tectonic setting of continental riftogenesis during a geologically short period. The age of acid volcanics can be treated as the age of formation of the lower and central parts of the section of the Sumian–Sariolian complex (2432 ± 22 Ma, U-Pb method, zircons). This age is close to that of the crystallization of their intrusive comagmates (the granites of the Nuorunen massif with an age of 2450 + 72 Ma, determined using U-Pb method on zircons), and it also practically corresponds (within the analytical errors) to the age of the zircons in the cement of the lava breccia unconformably overlying the upper horizons of the layered Lukkulaisvaara intrusion, 2442 ± 1 Ma old (U-Pb age on zircon). The data described in this paper testify to the formation in northern Kareliya of the Lower Proterozoic riftogenic volcanic-plutonic complex in the interval 2.45 - 2.40 Ga. The application of the K-Ar method allowed us to date the latest endogenic processes in the region as late and post-Svecofennian.

Table 3. Results of K-Ar method of study of minerals

No. of sample, mineral	Content of potassium, %	$^{40}Ar_{red} \times 10^{-9}$ g/g	$^{40}Ar/^{40}K$	τ K-Ar, Ma
63-ST, amphibole-1	0.12	23.36	0.163	1680 ± 20
63-ST, amphibole-2	0.20	37.71	0.159	1665 ± 20
63-ST, biotite	7.79	1250	0.134	1490 ± 15
15-2-ST, muscovite	9.07	1500	0.139	1520 ± 16

Note: The following values of constants were used: $\lambda_K = 0.581 \times 10^{-10}$ years^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ years^{-1}; $^{40}K = 1.167 \times 10^{-4}$ K of at. %.

Reviewer E.V. Bibikova

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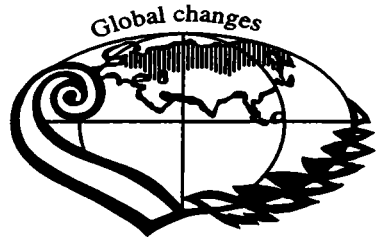

Evolution of the biosphere

Acritarchs of the Cambrian-Ordovician Boundary Deposits of the Baltic Phytoplankton Province

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Abstract – In the Baltic province, the Cambrian-Ordovician boundary deposits contain four acritarch assemblages: one of the Late Cambrian (LC4B), two of the early Tremadocian (OT1 and OT2), and one of the late Tremadocian (OT3). The Late Cambrian assemblage consists of the so-called Baltic taxa that are, thus far, known only in this province. Species characteristic of cold-water environments appear in the early Tremadocian assemblages, and the late Tremadocian taxa are represented by both cryophilic and thermophilic forms.

Key words: *Acritarchs, biostratigraphy, Late Cambrian, Early Ordovician, East European platform, and Baltic province.*

This paper is intended to discuss the taxonomic composition of acritarchs from the Cambrian-Ordovician boundary deposits of the Baltic phytoplankton province, namely, from the interval comprising the upper part of the *Peltura* Superzone and the Tremadocian stage. In the East European platform (Fig. 1), acritarchs from this level are known in several sections of the Yaroslavl', Leningrad, and Arkhangel'sk regions and near the clint belt of Estonia (Borovko *et al.*, 1984; Volkova and Mens, 1988; Volkova, 1989a, 1989b, 1990, 1993a; Verichev *et al.*, 1990). In addition, the Cambrian-Ordovician acritarchs of the Baltic province have been distinguished on Öland Island, Sweden (Bagnoli *et al.*, 1988; Di Milia *et al.*, 1989; Tongiorgi and Ribecai, 1990), and in northern Norway (Welsch, 1986).

The Cambrian-Ordovician boundary is not precisely defined. According to recent viewpoints (Kaljo *et al.*, 1990; Apollonov, 1992), its position within the conodont *Cordylodus andresi–C. lindstroemi* Zone is assumed to correspond to different levels; in the opinion of many researchers of the former USSR, it seems reasonable to place this boundary at the base of the *C. proavus* Zone (Apollonov, 1992; Dubinina, 1993). The second level is accepted in the current study.

The taxonomic composition of acritarch assemblages occurring in the Upper Cambrian deposits of the East European platform up to the *Leptoplastus* Zone is very similar to that known for synchronous formations of eastern Newfoundland (Volkova, 1990). Acritarchs from the overlying *Peltura* Superzone of this region predominantly belong to local taxa characteristic of the Baltic province. In this superzone, I distinguish two Late Cambrian assembalges: LC4A, in which *Impluviculus villosiusculus, Lusatia*, and *Striatotheca loculifera* are typical of its lower part, and LC4B, in which *Dasydiacrodium palmatilobum, Izhoria angulata*, and *Oodium rossicum* occur higher (Volkova, 1990). The first assemblage, which has an unusual composition, has so far been encountered only in the Yaroslavl' area; this fauna is out of the scope of the present work. The interval above it (the upper *Peltura* Superzone–Tremadocian Stage) contains four assemblages: LC4B of the Late Cambrian and three others of Tremadocian age that are indicated here as OT1, OT2, and OT3. Lists of taxa distinguished in all of these assemblages were published earlier (Volkova, 1989a, 1989b, 1990, 1993a), and this work is intended to determine principal changes in the taxonomic composition of acritarch assemblages at the Cambrian-Ordovician boundary.

Assemblage LC4B (Plate I) was discovered in the following units and localities: the Ladoga Formation, Leningrad region; the middle part of the Bugino Formation, Yaroslavl' region; the lower Maardu Member of the clint belt of Estonia (*Proconodontus* and *Cordylodus andresi* conodont zones); the Turjekelder and Vihula localities (samples 17/10 - 17/13); and the Tsitre Formation, well Maardu-56 (Volkova, 1989a, 1990, 1993a). The age of the assemblage was determined using trilobites *Parabolina jaroslavica* discovered in the middle part of the Bugino Formation and conodonts that occur

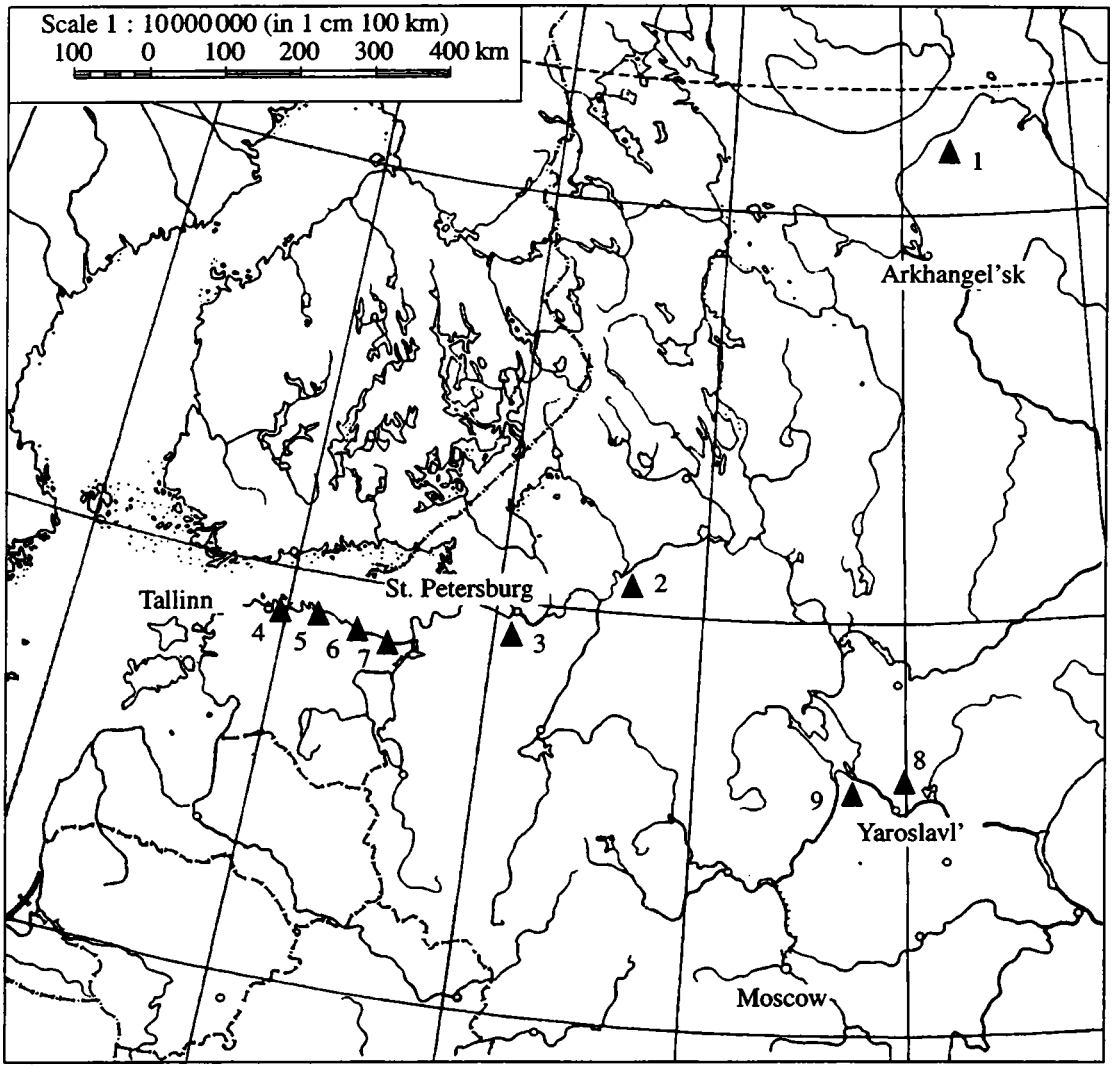


Fig. 1. Studied localities of Cambrian-Ordovician boundary deposits in the East European platform: 1 – well 1303; 2 – Syas' River; 3 – Izhora River; 4 – wells Maardu-9 and Maardu-56 and Suhkrumägi locality; 5 – Turjekelder; 6 – Vihula; 7 – Toila; 8 – well Tolbukhino-1; 9 – well Rybinskaya-1.

in the lower Maardu Member of Estonian sections from the upper *Peltura* Superzone up to the lower *Acerocare* Zone (Fig. 2). The assemblage includes many Baltic taxa typical of this province. The stratigraphic range of such species as *Calyxiella izhoriensis* Golub et Volk., *Cristallinium pilosum* Golub et Volk., *Nellia longiuscula* Golub et Volk., *N. magna* Volk., *Oodium rossicum* Tim., *O. timofeevii* Loeblich, *Vogtlandia petropolitana* (German) Volk., and *V. notabilis* Volk. is restricted to the aforementioned interval only. Other Baltic species transiting into the lower Tremadocian afford peculiar features to the acritarch assemblages of this level. These species include *Acanthodiacrodium timofeevii* Golub et Volk., *Baltisphaeridium capillatum* (Naum.) N. Umn., *Dasydiacrodium palmatilobum* Tim., *Elenia armillata* (Vanderflit) Volk., *Izhoria angulata* Golub et Volk., *Ladogella rotundiformis* Golub et Volk., *Schizodiacrodium armatum* Volk., *S. brevicrinitum* Golub et Volk., *S. fibrosum* Golub et Volk., and *Raphesphaera striatula* Volk. Acritarchs similar in composition to assemblage LC4B were identified in the upper *Peltura scarabaeoides* Zone of the Degerhamn section, Öland Island, Sweden (Di Milia *et al.*, 1989; Tongiorgi and Ribecai, 1990). Their assemblage (DGH 1b) also includes typical Baltic taxa: *Acanthodiacrodium timofeevii, Calyxiella izhoriensis, Cristallinium pilosum, Elenia armillata, Ladogella rotundiformis*, and *Schizodiacrodium fibrosum*. Several Baltic taxa characteristic of assemblage LC4B were also recognized in the upper part of the Digermul Group of northern Norway (microflora AVa; Welsch, 1986). These forms are represented by *Oodium rossicum; Multiplicisphaeridium cervinacornua* Welsch (= *Vogtlandia notabilis*); *Acanthodiacrodium digermulense* Welsch (= *S. armatum*); and

A. cf. *A. spinum* Rasul, which is similar to *A. timofeevii*. As I have already noted (Vol-kova, 1993a), this microflora should be referred to the Upper Cambrian rather than the Tremadocian.

In the temperate Baltic province, the Late Cambrian phytoplankton was fairly diverse. It comprised over 50 taxa, many of which were typical of this province only. In its taxonomic composition, this phytoplankton notably differed from the cold-water community of the Mediterranean province, exemplified by phytoplankton of eastern Newfoundland (Martin and Dean, 1981, 1988), and from the warm-water acritarchs reported from the Dayangcha locality of northeastern China (Yin, 1986). The phytoplankton species from the Baltic province were twice as diverse, and they included a small number of cosmopolitan forms [*Cristallinium cambriense* (Slavikova) Vang., *Stellechinatum uncinatum* (Downie) Martin, and others].

The early Tremadocian assemblages were collected from deposits corresponding to the *Cordylodus proavus* and *C. lindstroemi–C. angulatus/C. rotundatus* zones (Volkova and Mens, 1988; Volkova, 1989a, 1989b). Acritarchs from the *C. intermedius* Zone are unknown, and the stratigraphic boundaries between the early Tremadocian assemblages are unclear (Fig. 1).

The early Tremadocian assemblage OT1 (Plate II) with *Acanthodiacrodium angustum, Dicrodiacrodium ornatum, D. ramusculosum*, and *Arbusculidium striatulum* was collected from deposits of the *C. proavus* Zone in Estonia (the Maardu Member of localities Suhkrumägi and Maardu-9; Maardu and Suurjögi members of the Vihula locality, samples 17/7 and 49/4) and from the upper Bugino Subformation (well Rybinskaya-1, Yaroslavl' region). Formerly, typical Tremadocian acritarchs from these sections, excluding the Suhkrumägi locality, were included into the Cambrian-Tremadocian assemblage LC5 along with acritarchs from the *Cordylodus andresi* Zone (Vihula locality, samples 17/10 - 17/13), which lacks Tremadocian species (Volkova, 1990). It is more correct to consider species from the *C. andresi* Zone composing LC4B, as a separate Late Cambrian assemblage (Volkova, 1989a).

The early Tremadocian assemblage OT1 marks the first occurrence level of species typical of the cold-water Mediterranean province and is represented by the following forms: *Acanthodiacrodium angustum* (Downie) Combaz, *A. comptulum* Rasul, *Dasydiacrodium tumidum* (Deunff) Tongiorgi, *Dicrodiacrodium ornatum* (Combaz), and *D. ramusculosum* (Combaz) Volk.

A. angustum is the most widespread species among the aforementioned forms. It is known (Fig. 3) from the Tremadocian deposits of England (Downie, 1958; Rasul and Downie, 1974), France (Martin, 1973), Belgium (Vanguestaine, 1974; Martin, 1977), Spain (Wolf, 1980), Italy (Pittau, 1990), North Africa (Combaz, 1967; Jardine *et al.*, 1974), northern Iran (Ghavidel-Syooki, 1992), eastern Newfoundland (Martin, 1982), and northwestern Argentina (Bultynck and Martin, 1982). Other taxa have smaller distribution areas. For instance, *A. comptulum* has been encountered in the Tremadocian strata of England (Rasul, 1979) and North Africa (Elaouad-Debbaj, 1988). Specimens of *D. tumidum* occur in England (Rasul, 1979), North Africa (Deunff, 1961; Combaz, 1967; Jardine *et al.*, 1974), and Sweden (Bagnoli *et al.*, 1988), while *D. ornatum* and *D. ramusculosum* are known from North Africa (Combaz, 1967; Jardine *et al.*, 1974). The distribution of the forms *Arbusculidium striatulum* Volk. and *Multiplicisphaeridium* sp. 1, which appear for the first time, is restricted to the level of the Baltic assemblage OT1 (the table). Taking into account the appearance of these taxa, one may suggest that the lower boundary of assemblage OT1 coincides with the base of the *C. proavus* Zone, because in the Suhkrumägi section, the first occurrence of typical Tremadocian species (*A. angustum, A. comptulum, D. tumidum*, and *D. ornatum*) is confined to this level (Volkova and Mens, 1988).

Assemblage OT1 retains many features characteristic of the Late Cambrian assemblage LC4B. Here, we still observe a group of Baltic species, such as

Plate I. Late Cambrian acritarchs (the upper part of the *Peltura* Superzone, assemblage LC4B; scale bar 10 μm for all figures).
1 – *Schizodiacrodium armatum* Volk.; spec. GIN 3940/3498-1; Leningrad region; locality on the left bank of the Izhora River; sample 6B; Ladoga Fm. (0.9 m above the base); 2 – *Acanthodiacrodium timofeevii* Golub et Volk.; spec. GIN 3940/3497-6; Leningrad region; locality on the left bank of the Izhora River; sample 5B; Ladoga Fm. (0.3 m above the base); 3 – *Oodium rossicum* Tim.; spec. GIN 3940/3510-1; Leningrad region; locality on the right bank of the Izhora River; sample 12B; the Ladoga Fm. roof; 4 – *Ladogella rotundiformis* Golub et Volk.; spec. GIN 3940/3509-1; Leningrad region; locality on the right bank of the Izhora River; sample 11B; Ladoga Fm. (0.2 - 0.3 m above the base); 5 – *Schizodiacrodium brevicrinitum* Golub et Volk.; spec. GIN 3940/3497-8; Leningrad region; locality on the left bank of the Izhora River; sample 5B; Ladoga Fm. (0.3 m above the base); 6 – *Elenia armillata* (Vanderflit) Volk.; spec. GIN 3939/2865-3; Yaroslavl' region; well Tolbukhino-1, interval of 2080.2 - 2088.2 m; Bugino Fm. (3 m above the base); 7 – *Nellia longiuscula* Golub et Volk.; spec. GIN 3940/3497-8; Leningrad region; locality on the left bank of the Izhora River; sample 5B; Ladoga Fm. (0.3 m above the base); 8 – *Nellia magna* Volk.; spec. GIN 3939/3199-1; Yaroslavl' region; well Tolbukhino-1; interval of 2063.7 - 2071.7 m, basal portion; Bugino Fm.; 9 – *Dasydiacrodium palmatilobum* Tim.; spec. GIN 3939/3200-1; Yaroslavl' region; well Tolbukhino-1; interval 2080.2 - 2088.2 m, top portion; Bugino Fm.; 10 – *Vogtlandia notabilis* Volk.; spec. GIN 3940/3510-1; Leningrad region; locality on the right bank of the Izhora River; sample 12B; Ladoga Fm. roof; 11 – *Calyxiella izhoriensis* Golub et Volk.; spec. GIN 3940/3497-6; Leningrad region; locality on the left bank of the Izhora River; sample 5B; Ladoga Fm. (0.3 m above the base); 12 – *Izhoria angulata* Golub et Volk.; spec. GIN 3939/3200-1; Yaroslavl' region; well Tolbukhino-1; interval 2080.2 - 2088.2 m, top portion; Bugino Fm.; 13 – *Schizodiacrodium fibrosum* Golub et Volk.; spec. GIN 3939/3200-1; the same locality as above; 14 – *Baltisphaeridium capillatum* (Naum.) N. Umn.; spec. GIN 3939/3203-1; Yaroslavl' region; well Tolbukhino-1; interval 2080.2 - 2088.2 m, basal portion; Bugino Fm.

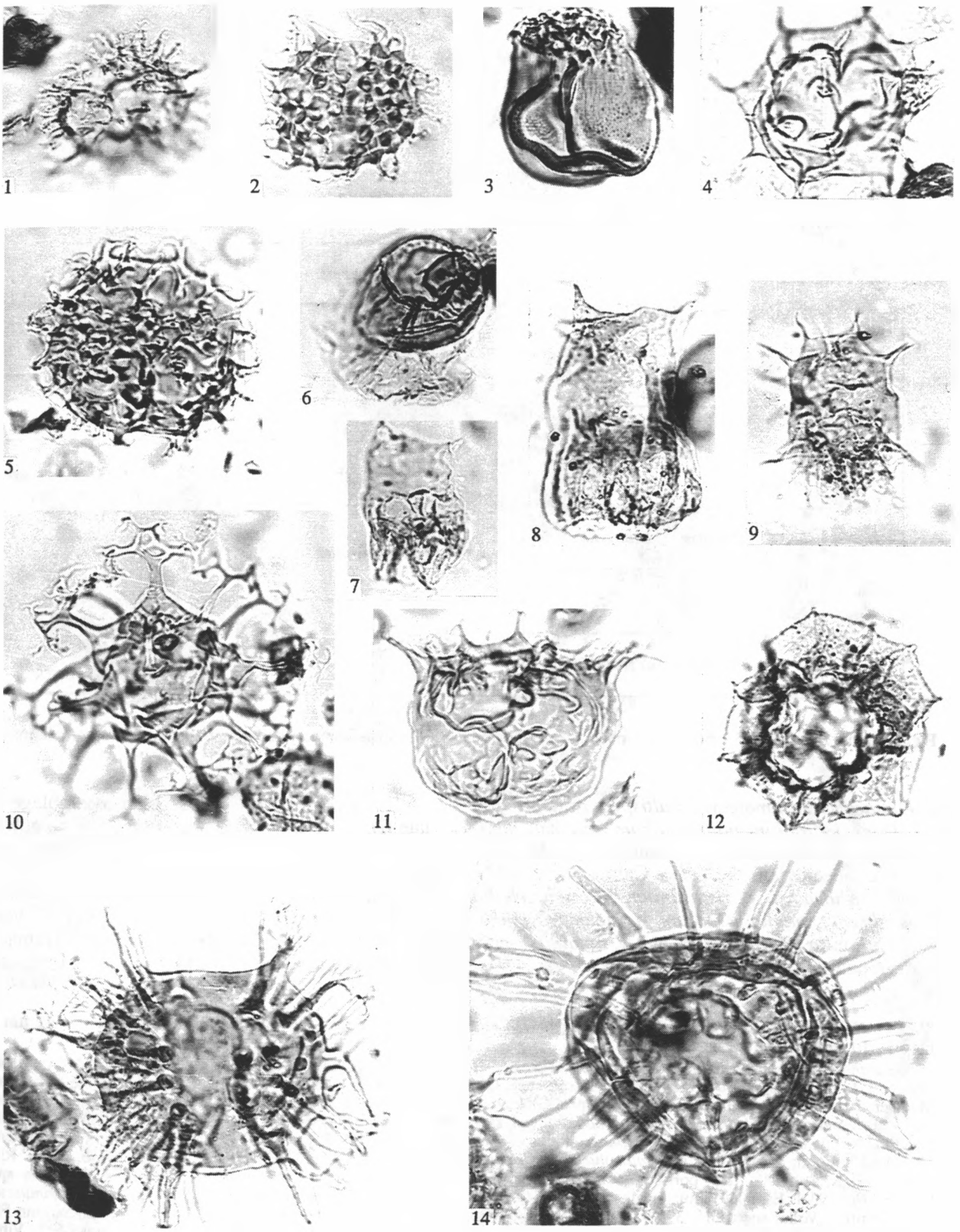


Plate I.

Age	Horizon	Trilobite and graptolite zones		Conodont zones	Acritarch assemblages
O_1t	Ceratopyge Horizon	*Clonograptus–Didymograptus*		*Drepanoistodus deltifer pristinus*	OT3
				Cordylodus rotundatus–C. angulatus	OT2
	Pakerort Horizon	*Rhabdinopora flabelliformis* s. l.		*C. lindstroemi*	
				C. intermedius	?
				C. proavus	OT1
		Acerocare		*C. andresi*	LC4B
ϵ_3	?	*Peltura*	*Peltura scarabaeoides*	*Proconodontus*	
			P. minor		
			Protopeltura praecursor		

Fig. 2. Faunal zonation and acritarch assemblages from Cambrian–Ordovician boundary deposits in the East European platform.

Acanthodiacrodium timofeevii, Baltisphaeridium capillatum, Dasydiacrodium palmatilobum, Izhoria angulata, and others (the table). Simultaneously, many typical Baltic species of the Late Cambrian, namely, *Calyxiella izhoriensis, Cristallinium pilosum, Nellia longiuscula, N. magna, Oodium rossicum, O. timofeevii, Vogtlandia petropolitana*, and *V. notabilis*, seem to be disappearing at this level (the table).

The second early Tremadocian assemblage (OT2, Plate II), containing *Vulcanisphaera britannica, V. imparila*, and *Baltisphaeridium setaceum*, is known from two sections of the Baltic–Ladoga clint (Volkova, 1989b) and from the Ordovician deposits that are penetrated by a well in the northern Arkhangel'sk region (Verichev *et al.*, 1990). An impoverished early Tremadocian assemblage from the Maardu-56 well, Estonia, should

Plate II. Early Tremadocian acritarchs (assemblages OT1 and OT2) from the East European platform (scale bar 10 - 12 μm for Figs. 1 - 10, and 50 μm for Fig. 11).

1 – *Acanthodiacrodium comptulum* Rasul; spec. GIN 3937/06880-1; Estonia; Suhkrumägi locality; sample Su-84-1A; Maardu Member; 2 – *Vulcanisphaera britannica* f. 1 Rasul; spec. GIN 3937/06378-2; Estonia; Toila locality; sample E45/8A; Lahemaa Member; 3 – *Arbusculidium striatulum* Volk.; spec. GIN 3937/06393-1; Estonia; Vihula locality; sample E49/4; Pakerort Horizon, Suurjögi Member; 4 – *Vulcanisphaera imparila* f. 4 Rasul; spec. GIN 3937/06377-4; Estonia; Toila locality; sample E45/9A; Lahemaa Fm., Vihula Member; 5 – *Multiplicisphaeridium* sp.1; spec. GIN 3939/3469-2; Yaroslavl' region; well Rybinskaya-1; interval 1785.4 - 1793.4 m; Bugino Fm.; 6 – *Baltisphaeridium setaceum* (Tim.); spec. GIN 3937/06343-2; Leningrad region; Syas' River locality; sample L-18/6; top portion of the Koporye Fm.; 7 – *Acanthodiacrodium angustum* (Downie) Combaz; spec. GIN 3937/06393-1; Estonia; Vihula locality; sample E49/4; Pakerort Horizon, Suurjögi Member; 8 – *Dicrodiacrodium ramusculosum* (Combaz) Volk.; spec. GIN 3939/3469-2; Yaroslavl' region; well Rybinskaya-1; interval 1785.4 - 1793.4 m, Bugino Fm.; 9 – *Baltisphaeridium aciculare* (Tim.); spec. GIN 3937/06378-2; Estonia; Toila locality; sample E45/8A; Lahemaa Fm., Vihula Member; 10 – *Acanthodiacrodium ubui* Martin; spec. GIN 3937/06377-4; Estonia; Toila locality; sample E45/9A; Lahemaa Fm., Vihula Member; 11 – *Lunulidia lunula* (Eis.) Eis.; spec. GIN 3937/06880-1; Estonia; Suhkrumägi locality; sample Su-84-1A; Maardu Member; 12 – *Brochos eisenackii* Vanderflit et Mikhailova; spec. GIN 3937/06343-2; Leningrad region; Syas' River locality; sample L-19/6; top portion of the Koporye Fm.

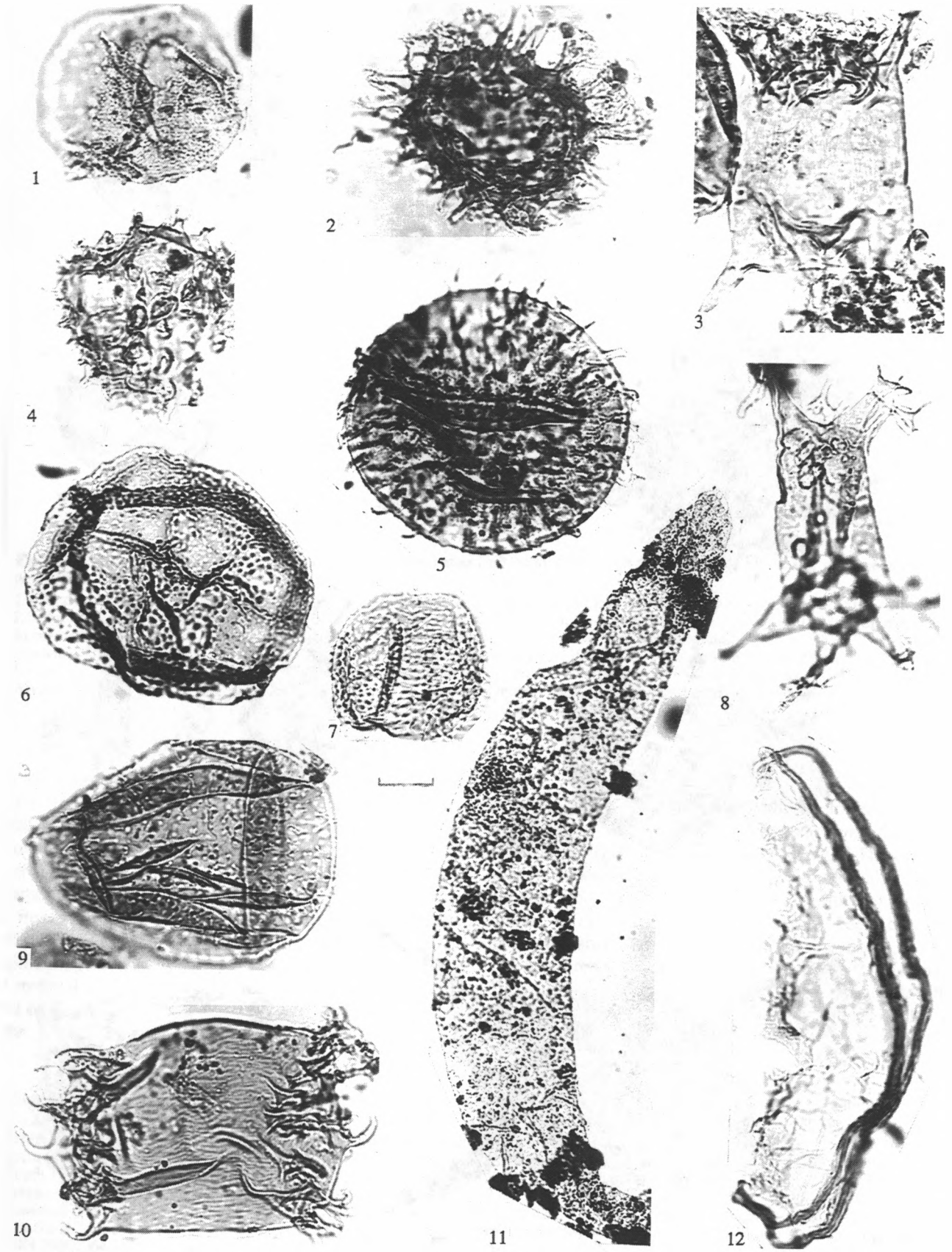
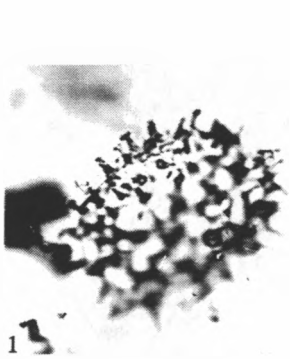


Plate II.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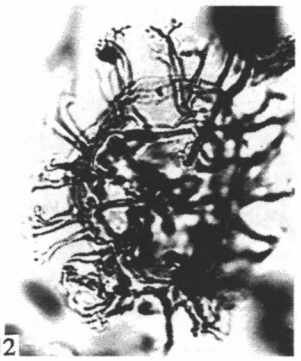
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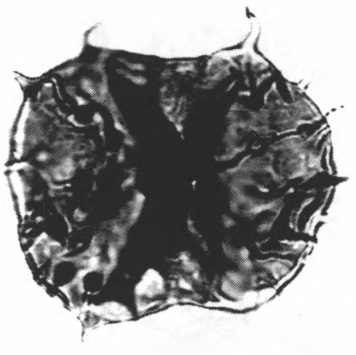
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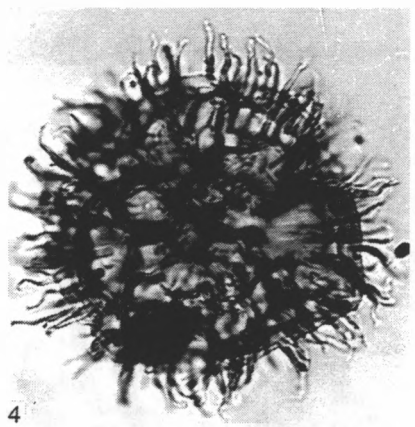
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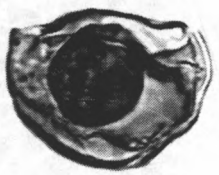
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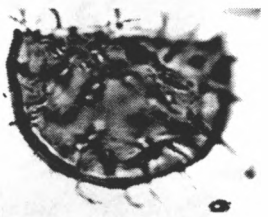
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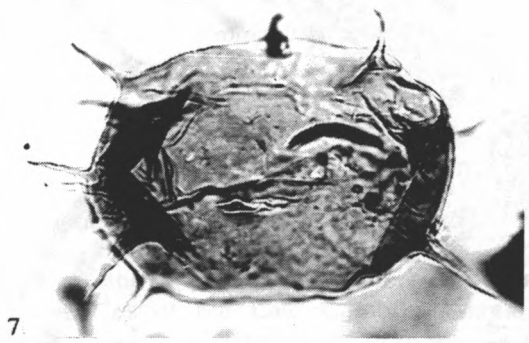
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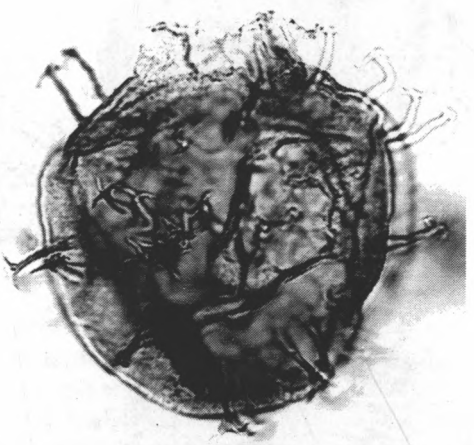
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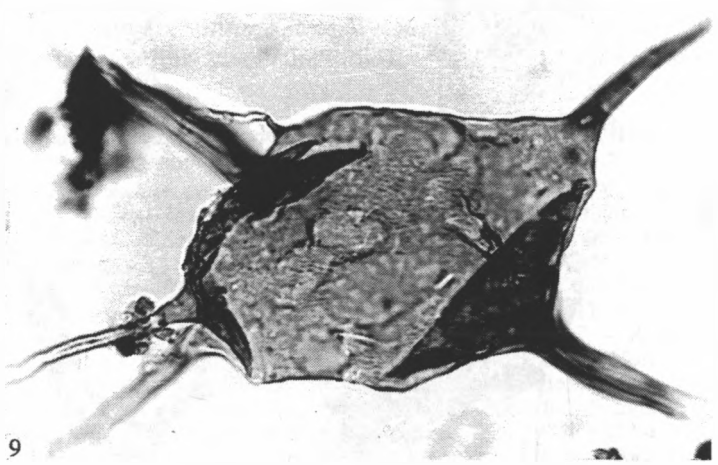
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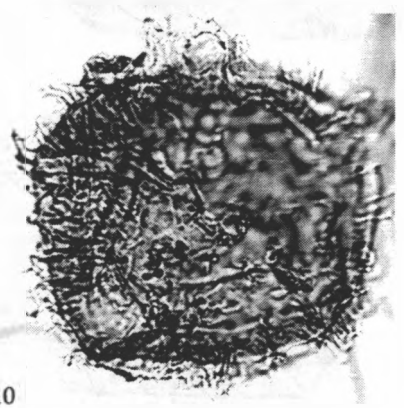
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Plate III.

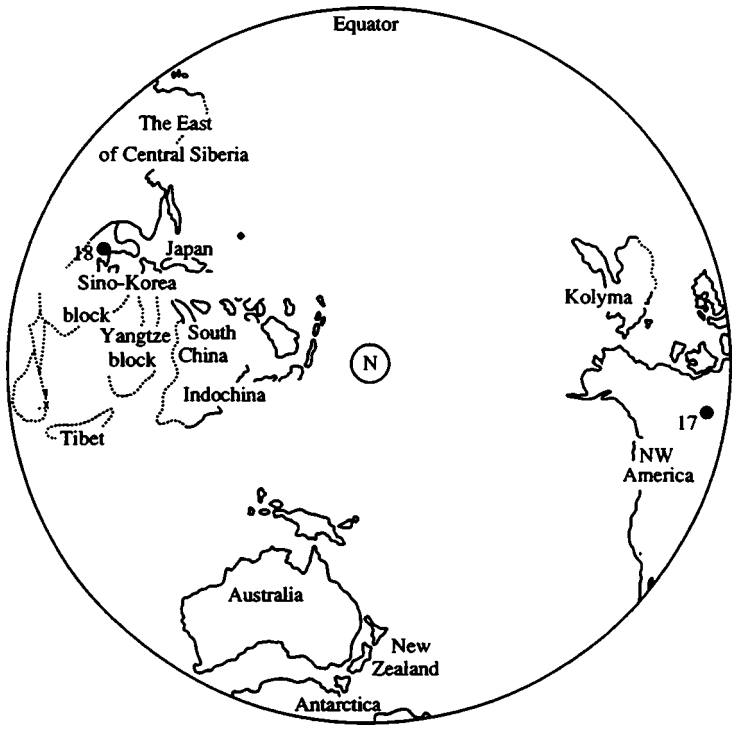

Fig. 3. Palinspastic map for the Early Ordovician (modified after Erdtmann, 1986) with the following localities of the Tremadocian acritarchs.

1 – Russia, Arkhangel'sk region (Verichev *et al.*, 1990; Volkova and Sivertseva, 1991); 2 – northern Norway (Welsch, 1986); 3 – Russia, Leningrad region (Volkova, 1989b); 4 – Russia, Yaroslavl' region (this work); 5 – Estonia (Volkova, 1989a,b, 1993a; Volkova and Mens, 1988); 6 – Sweden (Bagnoli *et al.*, 1988); 7 – Poland (Gorka, 1969); 8 – eastern Newfoundland (Martin, 1982); 9 – England (Downie, 1958; Rasul and Downie, 1974: Rasul, 1979; Molyneux and Rushton, 1988); 10 – France and Belgium (Martin, 1973, 1977; Vanguestaine, 1974); 11 – Spain (Wolf, 1980); 12 – Italy (Pittau, 1990); 13 – Northern Iran (Ghavidel-Syooki, 1992); 14 – North Africa (Deunff, 1961; Combaz, 1967; Jardine *et al.*, 1974; Elaouad-Debbaj, 1988); 15 – northwestern Argentina (Bultynck and Martin, 1982); 16 – Texas, USA (Barker and Miller, 1982); 17 – Alberta, Canada (Martin, 1984, 1992); 18 – Jilin province, China (Yin, 1986; Martin and Yin, 1988).

also be referred to this assemblage (Volkova, 1993a). At the Baltic–Ladoga clint, the assemblage OT2 was extracted from the Lahemaa Formation (the Toila locality of Estonia) and the Koporye Formation (the Syas' River locality, Leningrad region). According to conodonts, the age of both formations corresponds to the interval of the *Cordylodus lindstroemi–C. angulatus/C. rotundatus* zones (*Opornye ...*, 1989). The stratigraphic range of assemblage OT2 probably corresponds to this interval also (Fig. 2). It represents the first occurrence level of the following forms: *Vulcanisphaera britannica* Rasul, *V. imparila* Rasul, *Acanthodiacrodium ubui* Martin, *Actinotodissus sicaformis* (Molyneux) Siverz. et Volk., *Caldariola glabra* (Martin) Molyneux, *Baltisphaeridium aciculare* (Tim.), *B. setaceum* (Tim.), and *Dictyotidium? operculatum* Siverz. et Volk. The first two species occur only within the indicated interval. They are known from the Tremadocian deposits of England (Rasul, 1979), and *V. britannica* has also been identified in coeval strata of Morocco (Elaouad-Debbaj, 1988). The last three species have so far been encountered in the Tremadocian sediments of the East European platform (Timofeev, 1959; Volkova and Sivertseva, 1991). The most widespread form among these is *A. ubui*,

Plate III. Late Tremadocian acritarchs (assemblage OT3) from the East European platform (scale bar 10 μm for all figures).

1 – *Athabascaella rossii* Martin emend. Martin et Yin; spec. GIN 3937/06401-2; sample 545, depth 133.1 m; 2 – *Athabascaella playfordii* Martin emend. Martin et Yin; spec. GIN 3937/06401-2; sample 545, depth 133.1 m; 3 – *Acanthodiacrodium formosum* Gorka; spec. GIN 3937/06400-3; sample 542, depth 132.8 m; 4 – *Athabascaella penica* Martin et Yin; spec. GIN 3937/06400-3; sample 542, depth 132.8 m; 5 – *Caldariola glabra* (Martin) Molyneux; spec. GIN 3937/06402-3; sample 546, depth 133.4 m; 6 – *Stelliferidium furcatum* (Deunff) emend. Deunff, Gorka et Rauscher; spec. GIN 3937/06402-3; sample 546, depth 133.4 m; 7 – *Dasydiacrodium tumidum* (Deunff) Tongiorgi; spec. GIN 3937/06404-3; sample 548, depth 133.9 m; 8 – *Aryballomorpha grootaertii* Martin emend. Martin et Yin; spec. GIN 3937/06400-3; sample 542, depth 132.8 m; 9 – *Dasydiacrodium tremadocum* (Gorka) Tongiorgi; spec. GIN 3937/06400-3; sample 542, depth 132.8 m; 10 – *Aryballomorpha* sp.; spec. GIN 3937/06399-2; sample 541, depth 132.0 m.

All exemplars are from the Varangu Fm., well Maardu-56, Estonia.

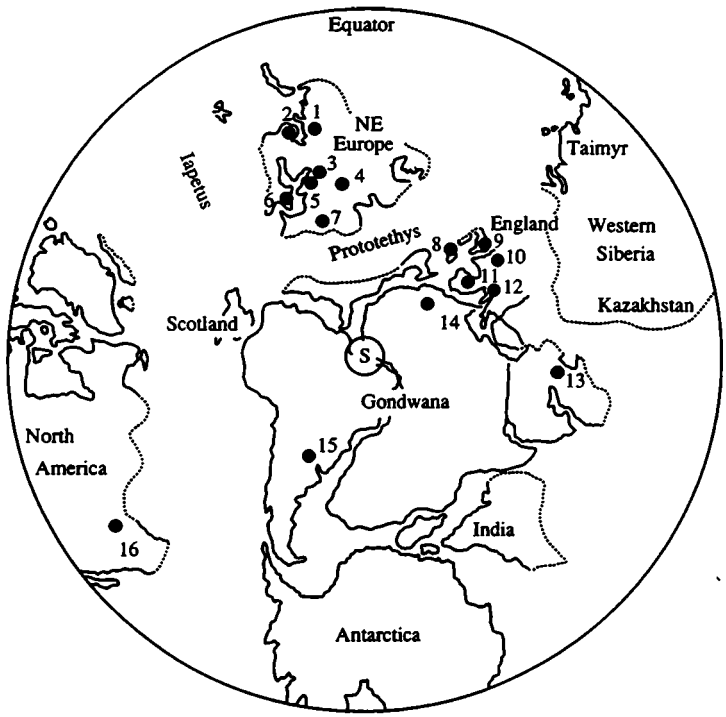

Fig. 3. (Contd.).

which occurs in the Cambrian-Tremadocian rocks of eastern Newfoundland (Martin, 1982) and in the Tremadocian formations of England, Belgium, France, Spain, Algeria, Morocco, Sweden, and northern Norway (Bagnoli *et al.*, 1988; Elaouad-Debbaj, 1988). *A. sicaformis* has been reported from the Tremadocian-Arenigian beds of England (Molyneux and Rushton, 1988), and *C. glabra* is known within the following stratigraphic intervals: the Tremadocian in France (Martin, 1973) and Spain (Wolf, 1980), the middle-upper Tremadocian in Sweden (Bagnoli *et al.*, 1988) and the Tremadocian-Arenigian in England (Molyneux and Rushton, 1988). The assemblage under consideration contains a significantly smaller amount of Baltic species that originated in the terminal Cambrian time. It lacks such forms as *Dasydiacrodium palmatilobum, Izhoria angulata*, and *Ladogella rotundiformis* and species of the *Schizodiacrodium* genus. The existing Baltic acritarchs are represented by *B. capillatum, E. armillata, Raphesphaera striatula*, and *Lunulidia lunula* Eis.; the latter species is restricted in distribution to the Tremadocian (the table).

Thus, the early Tremadocian acritarch assemblages show the coexistence of taxa typical of both the cold-water Mediterranean province and the Baltic regions inhabited by some species inherited from the Late Cambrian. No taxa characteristic of the warm Tremadocian provinces have been recognized in their composition. Acritarchs of this type dwelt in the Jilin province, northeastern China (Yin, 1986) and populated the Alberta province in Canada (Martin, 1992). It is likely that, in the early Tremadocian time, the migration of thermophilic phytoplankton into temperate latitudes was either very limited or even interrupted. As I noted earlier (Volkova, 1993c), the Baltic and Mediterranean provinces of the early Tremadocian time were certainly similar in that their taxonomic composition of phytoplankton was dominated by representatives of subgroups Diacromorphitae and Herkomorphitae. However, the respective acritarch assemblages from the Baltic province do not reveal any distinct similarities with the phytoplankton that characterizes the local acritarch zonation of the Tremadocian deposits in England (Rasul, 1979) and North Africa (Jardine *et al.*, 1974; Elaouad-Debbaj, 1988).

The late Tremadocian assemblage OT3 (Plate III) with *Aryballomorpha grootaertii, Athabascaella playfordii*, and *Dasydiacrodium tremadocum* was distinguished in the Varangu Formation, recovered from the Maardu-56 well in Estonia. Originally, I referred this assemblage to the middle-upper Tremadocian (Volkova, 1993a); later, I restated its age as the late Tremadocian (Volkova, 1993b), because Estonian geologists do not affirm the middle Tremadocian stratigraphic subdivision. The latter viewpoint is also accepted in the current work.

In the acritarch-bearing section of the Varangu Formation, faunal remains are unknown. In other sections of the Estonian clint, this formation yielded graptolites *Bryograptus* cf. *broeggeri* Monsen, *Clonograptus* cf. *tenellus* Linn., and *Adelograptus* cf. *hunnebergensis* (Moberg) along with conodonts *Drepanodus bysimmetricus* Viira, *D. pristinus* Viira, *D. amoenus* Lindstr., and others (*Opornye* ..., 1989).

Distribution of characteristic acritarch species in the Cambrian-Ordovician boundary deposits of the East European Platform

Taxa	Upper Cambrian, assemblage LC4B			Lower Tremadocian, assemblage OT1		Lower Tremadocian, assemblage OT2			Upper Tremadocian, assemblage OT3
	Yaroslavl' region (well Tolbukhino-1)	Leningrad region (localities at the Izhora River)	Estonia (localities: Vihula, sample 17/10-17/13; Turjekelder, well Maardu-56)	Yaroslavl' region (well Rybinskaya-1)	Estonia (localities: Vihula, samples 17/7 and 49/4; Suhkrumägi, well Maardu-9)	Leningrad region (localities at the Syas' River)	Estonia (locality Toila, well Maardu-56)	Arkhangel'sk region (well 1303)	Estonia (well Maardu-56)
	1	2	3	4	5	6	7	8	9
Calyxeilla izhoriensis	+	+							
Cristallinium pilosum	+	+	+						
Nellia longiuscula	+	+							
N. magna	+	+	+						
Oodium rossicum	+	+	+						
O. timofeevii	+	+							
Vogtlandia petropolitana	+	+							
V. notabilis	+	+	+						
Acanthodiacrodium timofeevii	+	+	+		+				
Dasydiacrodium palmatilobum	+	+	+	+	+				
Izhoria angulata	+	+	+	+	+				
Ladogella rotundiformis	+	+	+	+	+				
Schizodiacrodium armatum	+	+	+	+	+				
S. brevicrinitum	+	+	+		+				
S. fibrosum	+	+	+	+	+				
Timofeevia janischewskyi	+	+	+		+				
Vulcanisphaera aff. *V. capillata*			+	+					
Arbusculidium destombesii	+	+	+	+	+		+		
Baltisphaeridium capillatum	+	+	+	+	+		+		
Elenia armillata	+	+	+		+		+		
Raphesphaera striatula		+	+				+		
Stellechinatum uncinatum	+		+	+	+	+	+		
Timofeevia sp. 1	+	+	+				+		

(Contd.)

Taxa	Upper Cambrian, assemblage LC4B			Lower Tremadocian, assemblage OT1		Lower Tremadocian, assemblage OT2			Upper Tremadocian, assemblage OT3
	Yaroslavl' region (well Tolbukhino-1)	Leningrad region (localities at the Izhora River)	Estonia (localities: Vihula, sample 17/10-17/13; Turjekelder, well Maardu-56)	Yaroslavl' region (well Rybinskaya-1)	Estonia (localities: Vihula, samples 17/7 and 49/4; Suhkrumägi, well Maardu-9)	Leningrad region (localities at the Syas' River)	Estonia (locality Toila, well Maardu-56)	Arkhangel'sk region (well 1303)	Estonia (well Maardu-56)
	1	2	3	4	5	6	7	8	9
Arbusculidium striatulum					+				
Multiplicisphaeridium sp. 1				+	+				
Acanthodiacrodium comptulum					+	+	+		
Dicrodiacrodium ramusculosum + *D. ornatum*				+	+		+		
Lunulidia lunula					+		+		
Acanthodiacrodium angustum					+	+	+	+	+
Dasydiacrodium tumidum					+		+		+
Vulcanisphaera britannica							+		
V. imparila						+	+	+	
Acanthodiacrodium ubui						+	+	+	+
Actinotodissus sicaformis								+	+
Baltisphaeridium aciculare							+		+
B. setaceum						+	+		+
Caldariola glabra							+	+	+
Dictyotidium ? *operculatum*							+	+	+
Acanthodiacrodium formosum									+
Aryballomorpha grootaertii									+
Athabascaella penica									+
A. playfordii									+
A. rossii									+
Dasydiacrodium tremadocum									+
Stelliferidium furcatum									+
Brochos eisenackii			+		+	+	+	+	+

Note: 1, 2, 4 – Volkova, 1990; 3 – Volkova, 1989a, 1990, 1993; 5 – Volkova and Mens, 1988; Volkova, 1989a, 1990; 6, 7 – Volkova, 1989b, 1993; 8 – Verichev *et al.*, 1990; 9 – Volkova, 1993.

The upper Tremadocian marks notable changes in the taxonomic composition of acritarchs, because nearly all Baltic species, except for *B. aciculare, B. setaceum*, and *D.? operculatum*, disappear at this level. Another exception is *Brochos eisenackii*, whih has a peculiar morphology and is known since the Late Cambrian. The late Tremadocian assemblage shows a mixed composition. Here, taxa typical of warm equatorial basins coexist with species that inhabited the cold-water Mediterranean province. The first group includes *Aryballomorpha grootaertii* (Martin) emend. Martin et Yin, *Athabascaella penica* Martin et Yin, *A. playfordii* Martin, and *A. rossii* Martin. Upper Tremadocian deposits with these forms are known in northeastern China (Martin and Yin, 1988); Alberta province, Canada (Martin, 1984, 1992); and western Texas, USA (Barker and Miller, 1989). The cryophilic taxa typical of high latitudes are represented by *Acanthodiacrodium formosum* Gorka and *Dasydiacrodium tremadocum* (Gorka) Tongiorgi, both of which are also known from the upper Tremadocian deposits of Poland (Gorka, 1969) and England (Rasul, 1979). In addition, the assemblage includes abundant specimens of *Stelliferidium furcatum* (Deunff) emend. Deunff, Gorka et Rauscher, which is widespread in the Tremadocian of the Sahara (Deunff, 1961). A similar assemblage of mixed composition, which bears *A. grootaertii, A. playfordii*, and *D. tremadocum*, has also been distinguished in the upper Tremadocian deposits of Öland Island, Sweden (Bagnoli *et al.*, 1988).

Thus, the late Tremadocian was a time of the migration of thermophilic phytoplankton from the equatorial latitudes. This event, caused by climatic warming, is unrecognizable in the lower Tremadocian deposits.

Reviewer M.A. Akhmet'ev

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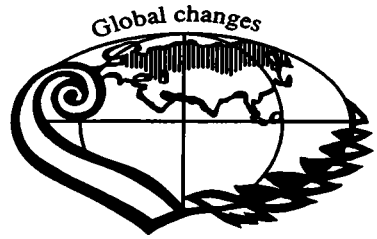

Evolution of the biosphere

Age Variability of Palynomorph Compositions of the Middle and Late Triassic of Syria and Their Relation to Climate and Facies

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Abstract – A succession of eight palynological assemblages designated by characteristic taxa were established in Middle to Upper Triassic carbonate and evaporite deposits in northwest and central Syria. A certain regularity in the distribution of the main palynomorph groups was observed in marine, coastal marine, and lagoon deposits. Palynomorphs, along with some types of rocks, served as indicators of climate and sedimentary environments.

Key words: *Stratigraphy, Triassic, palynology, paleogeography, and Syria.*

INTRODUCTION

Triassic deposits are widespread in Syria; however, they are rarely exposed. It was previously believed that they outcrop in the extreme northwest (the Bassit area) within the "ophiolite formation." Based on finds of *Halobia cassiana* Mojs., *H. comata* Bittn., and *Shafhautlia* sp. in the upper parts of these deposits, they were assigned to the Late Triassic (Ponikarov *et al.*, 1969). Later, an outcrop of Upper Triassic rocks in the Palmirids area was reported on the basis of a palynological study of several samples from the Jabel Hayan section. This is discussed below.

Triassic deposits were recognized in numerous wells in extensive areas of Syria: in the central, eastern, and northeastern regions. It was established that these deposits have a maximum thickness of up to several hundred meters in the northeast, within the Mesopotamia marginal depression. The thickness decreases to 200 - 100 meters westward and southward. Drilling enabled general features of the Triassic sequence to be recognized. All sections are represented by an alternation of carbonate and evaporite sediments with rare interbeds of variegated shales (black, gray, green, and red) and dolomitic clays.

The Triassic deposits of northeastern Syria are considered in the framework of the Kurachine, Butmah, Adaiyah, Muss, Alan, and Serjelu formations, which were first described in Iraq. Their age in the type sections of Iraq was insufficiently known because of the rare occurrence of fauna. Therefore, they were considered to be Jurassic in age, except the lowermost Kurachine Formation, which was assigned to the Late Triassic. In Syria, these formations were recognized on the basis of their lithology, and for a long time their age was determined through correlations with Iraqi sections (Ponikarov *et al.*, 1969). Studies of foraminifers, ostracods, and miospores from a number of Syrian wells put into question both the age of these formations and their correlations with the Iraqi sections (Bash Imam *et al.* 1978; Yaroshenko *et al.*, 1982; Bash Imam and Sigal, 1985).

Palynological studies along with the study of fauna were implemented in the paleontological laboratory of the Syrian Petroleum Company for the stratigraphic subdivision of Triassic deposits. The first finds of Triassic miospores were reported by Khoja (1972). The subsequent study of miospores from the central and northeastern regions made it possible to recognize five stratigraphic subdivisions that are the Early - Middle Triassic, Middle Triassic (presumably Anisian), Ladinian - Carnian, Norian, and Late Triassic - Early Jurassic in age (Yaroshenko *et al.*, 1982). Later, palynological studies, which were mainly performed in the northeastern region, led to the recognition of four subdivisions that are the late Anisian - early Ladinian, late Ladinian, Carnian, and Norian in age (Yaroshenko and Bash Imam, 1989).

Generalization and revision of the earlier studied assemblages provided higher resolution. A succession

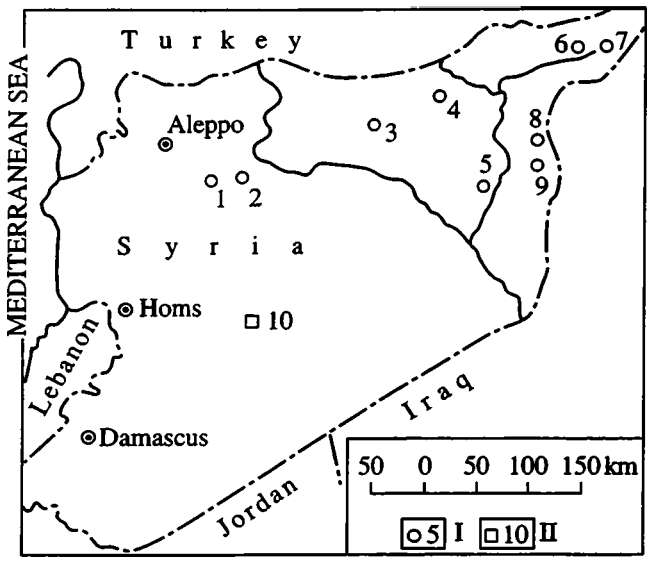

Fig. 1. Location scheme of sections. I – wells, II – exposures. 1 – Habari-1; 2 – Wahab-1; 3 – Abba-1; 4 – Afandi-1; 5 – Maaza-1; 6 – Khourbet-3; 7 – Rumelan-6; 8 – Jeribe-101; 9 – Gbeibeh-101; 10 – Jabel Hayan.

of eight palynological assemblages, designated by characteristic taxa, was established. The present article deals with the chronological variability, the details of palynomorph compositions, and the determination of the climate and sedimentation dependence of these assemblages.

MATERIALS AND METHODS

Forty core and bore mud samples from nine wells were palynologically studied. These wells, from the west to the east, are the following (Fig. 1): Wahab-1 (intervals 1791 - 1795 m and 2010 - 2040 m), Habari-1 (interval 1312 - 1337 m), Abba-1 (intervals 1873 - 1875 m, 1893 - 1896 m, 1912 - 1914 m, 1914 - 1915 m, 2119 - 2121 m, 2166 - 2181 m, and 2193 - 2214 m), Afandi-1 (intervals 2160 - 2166 m, 2178 - 2184 m, and 2184 - 2190 m), Maaza-1 (depths 2865.9 m, 2866.5 m, 2867.9 m, 2868.7 m, 2869.5 m, 2871.0 m, 2871.5 m, and 2873.0 m), Khourbet-3 (interval 2425 - 2429 m), Rumelan-6 (interval 2504 - 2524 m), Jeribe-101 (interval 4780 - 4790 m), and Gbeibeh-101 (intervals 3810 - 3830 m, 3970 - 3990 m, 4000 - 4025 m, and 4030 - 4050 m). Some isolated samples with a low content of miospores from wells Afandi-1, Tishrin-2, and Alian-2 were also used. Only one of the five samples from the Jabel Hayan section in the Palmirids contained miospores. Samples weighing as much as 20 - 50 g were represented by gray-colored rocks: shale, claystone, and clay. Samples were subjected to chemical treatment in compliance with the standard procedure using HCl, HF, KOH, and cadmium liquid. Slides were prepared using glycerine–gelatine. The slides are stored at the palynological laboratory of the Geological Institute, Russian Academy of Sciences. A *Zetopan Reichert* microscope was used for the palynological study. Miospores were photographed using an immersion ×100 objective. All stratigraphically significant palynomorphs are illustrated in Plates I - IV.

LITHOLOGICAL AND PALEONTOLOGICAL DATA

Sections of Triassic deposits in the central and eastern regions of Syria differ in their lithology. They are located within a number of formations that have different names. In the central region, the Triassic corresponds to a part of the "Mulussa" Formation, which is built of stratified limestones with interbeds of black clayey shales and has an overall thickness of up to 1300 m. The "Mulussa" Formation is barren of fossils except the Abba-1 section, where the Early Triassic *Pseudomonotis clarai* Emmr. was found in its base, and the Middle Triassic *Daonella moussoni* Mer. and *D. indica* Bittner were recorded higher in the section (Ponikarov *et al.*, 1969). In the eastern and northeastern regions of Syria, the Kurachine, Butmah, Adaiyah, Muss, and Alan formations and the lower part of the Serjelu formation are correlated with the Triassic.

The Kurachine Formation (400 - 600 m thick) unconformably overlies Upper Paleozoic deposits, formed of limestones and dolomites and subdivided into two parts. The lower and middle parts of the formation predominantly consist of dolomites. This part is called "Kurachine-dolomite." The upper part is mainly represented by anhydrites and is called "Kurachine-anhydrite." The Butmah Formation (150 m) conformably overlies the Kurachine Formation and is composed of recurrent alternations of dolomites (clayey and anhydritic)

Plate I.

1 – *Deltoidospora* sp., Maaza-1, 2867.9 m. 2 – *Concavisporites toralis* (Leschik) Nilsson, 1958, Maaza-1, 2871.5 m. 3 – *Kyrtomisporis speciosus* Mädler, 1964, Maaza-1, 2871.5 m. 4 – *Trachysporites asper* Nilsson, 1958, Maaza-1, 2867.9 m. 5 – *Dictyophyllidites harrisii* Coup., 1958, Maaza-1, 2871.5 m. 6 – *Rewanispora vermiculata* Ant. et Taug., 1973, Wahab-1, int. 1791 - 1795 m. 7 – *Triplexisporites playfordii* (de Jersey et Hamilton) Foster, 1979, Abba-1, int. 2166 - 2181 m. 8 – *Aratrisporites* sp., Afandi-1, int. 2178 - 2184 m. 9 – *Kyrtomisporis laevigatus* Mädler, 1964, Maaza-1. 2869.5 m. 10 – *Paracirculina scurrilis* Scheuring, 1970, Abba-1, int. 1873 - 1875 m. 11 – *Converrucosisporites cameroni* (de Jerssey) Playford et Dettmann, 1965, Gbebeh-101, int. 4000 - 4025 m. 12 – *Keuperisporites baculatus* Schulz, 1965, Afandi-1, int. 2184 - 2190 m. 13 – *Microreticulatisporites galli* Adloff et Doubinger, 1969, Abba-1, int. 1912 - 1914 m. 14 – *Tsugaepollenites? pseudomassulae* Mädler, 1964, Maaza-1, 2871.5 m. 15 – *Ovalipollis* sp., Maaza-1, 2871.5 m. 16 – *Densoisporites nejburgii* (Schulz) Balme, 1970, Afandi-1, int. 2178 - 2184 m. 17 – *Uvaesporites gadensis* Praehauser-Enzenberg, 1970, Abba-1, int. 1914 - 1915 m. 18 – *Corollina meyeriana* Klaus, 1960, Maaza-1, 2873 m. ×1000 for 1 - 11, and 13 - 18; ×500 for 12.

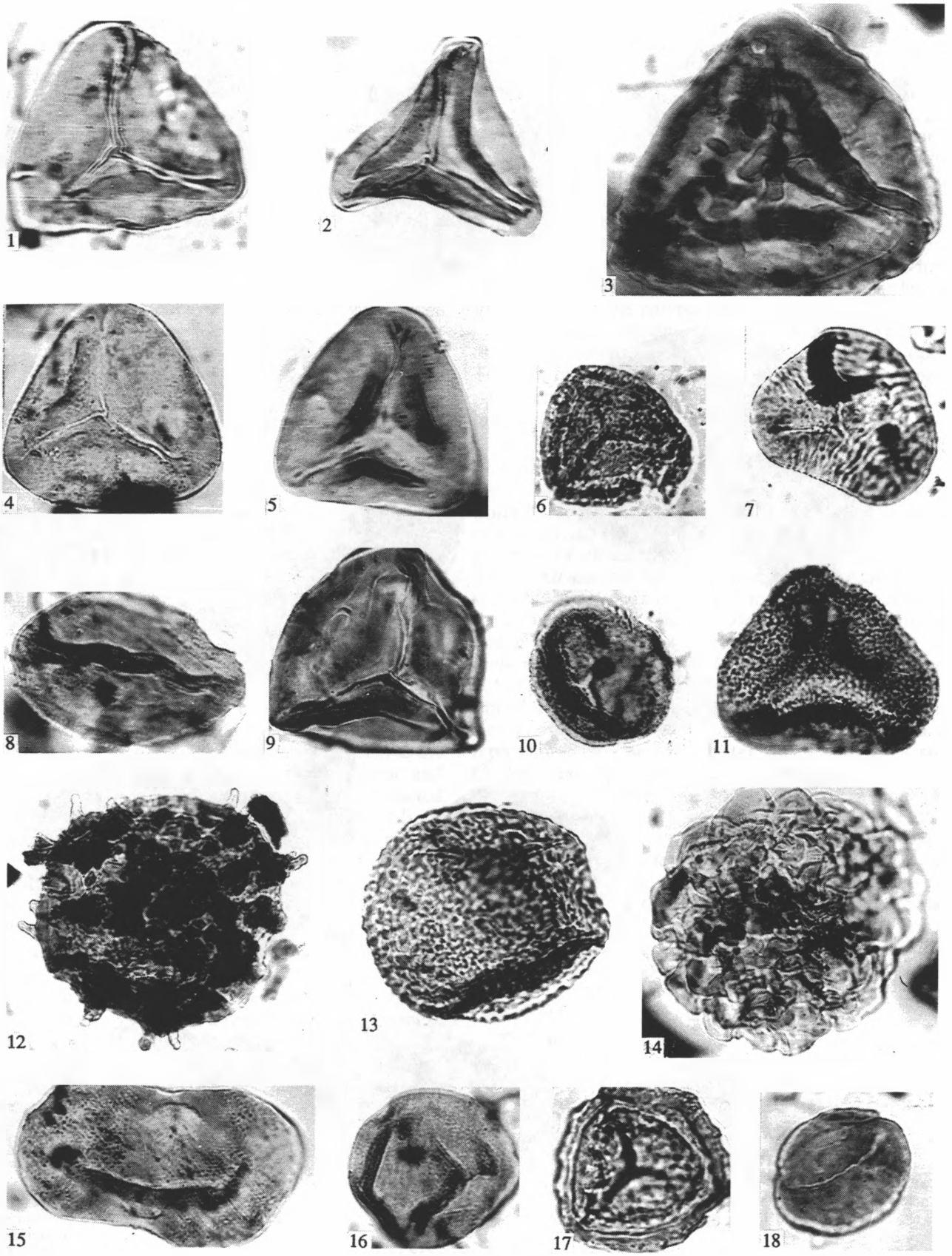

Plate I.

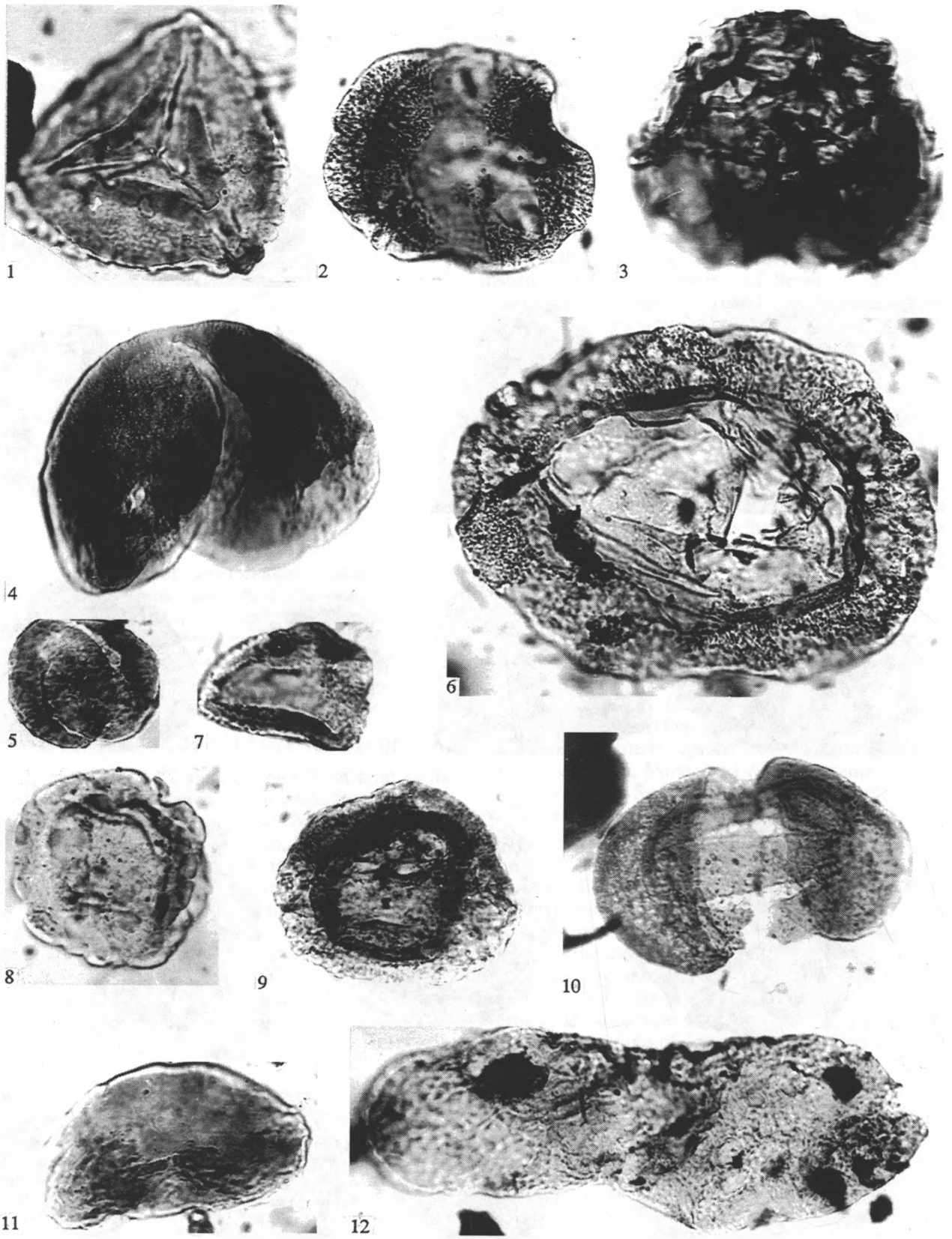

Plate II.

and clayey limestones with layers of variegated shales and anhydrites. The Adaiyah Formation (100 - 120 m) conformably covers the Butmah Formation and is represented by anhydrites with interbeds of clayey dolomites, variegated shales, and sometimes hypsum. The Muss Formation (50 - 70 m) conformably overlies the rocks of the Adaiyah Formation and is formed of gray and brown limestones, which are dolomitized in places, with interlayers of dolomites and hypsum. The conformably overlying Alan Formation (50 m) is represented by anhydrites with interbeds of dolomites and shales. The Serjelu Formation (600 m thick) conformably overlies the Alan Formation. It is built of dolomites and limestones, which alternate with shales and dolomitized clays.

Fossils in the considered deposits are represented by foraminifers and ostracods. Anisian foraminifers were found in a number of wells in the Kurachine Formation, and Ladinian–Carnian and Carnian forms were confined to the Butmah Formation (Bash Imam *et al.*, 1978). The species *Simeonella brotzenorum* Sohn. is worth mentioning among the ostracods. It is confined to the Butmah, Adaiyah, and Muss formations, which are correlated with the lower part of the Upper Triassic. The presence of this species in the "Mulussa" Formation in a number of wells on the Aleppo Plateau correlates them with sections in the northeast (Bash Imam and Sigal, 1985).

PALYNOLOGICAL CHARACTERISTICS

Palynological study of the Triassic deposits, which are predominantly represented by carbonate rocks, is extremely difficult because of difficulties related to the extraction of palynomorphs from the sediment and their poor preservation. Palynomorphs were extracted from thin gray shale and clay layers. The rarity of finds and the insufficient preservation of miospores in a number of samples are caused by the unfavorable burial conditions. Poor preservation hampered precise identification; therefore, some taxa were determined only at the generic level.

As was pointed out above, the present work deals with the refinement and supplementation of data obtained earlier (Yaroshenko *et al.*, 1982; Yaroshenko and Bash Imam, 1989). As a result, eight stratigraphic units, which were substantiated by successive assemblages of miospores and designated by typical taxa, were established. During this study, we considered the appearance level of taxa as well as their quantity. When additional materials are studied, these assemblages may serve as a foundation for the establishment of palynozones. The age of the assemblages was determined through comparison with palynofloras known from the type sections in the Alps, which are stratigraphically substantiated on the basis of ammonites, conodonts, and bivalves (Klaus, 1960, 1964; Mostler and Scheuring, 1974; Morbey, 1975; Schuurman, 1977, 1979; Dunay and Fisher, 1978; Scheuring, 1970, 1978; Visscher and Krystyn, 1978; Visscher and Brugman, 1981; Van de Eem, 1983). Palynological data on sections of Laurasia and Gondwana were also taken into account. The description of the assemblages is based on materials from the palynological laboratory of the Syrian Petroleum Company. Between 100 and 950 palynomorph specimens have been counted for each sample. The stratigraphic distribution of main palynomorphs, which emphasizes time-related changes of the assemblages, is given in Fig. 2.

The assemblage with *Densoisporites nejburgii–Lunatisporites pellucidus* (I) is recorded in deposits of the "Mulussa" Formation from the Wahab-1 well (interval 2010 - 2040 m) in the Aleppo Plateau area, central Syria. The assemblage is characterized by the presence of disaccate pollen of *Alisporites grouvogeli* Klaus, *Alisporites* sp., *Platysaccus queenslandi,* and sporadic *Vitreisporites* sp. and monosaccate pollen of *Accinctisporites* sp. and *Monosaccites* sp. *Triadispora,* which are fairly numerous. Rare specimens of *Stellapollenites thiergartii* (Mädler) Clement-Westerhof *et al.* are poorly preserved. The most characteristic ribbed forms are *Lunatisporites pellucidus* (Goubin) Helby, and *Lunatisporites* sp. Spores are scarce and represented by *Punctatisporites* sp., *Todisporites* sp., *Cyclotriletes* sp., and *Aratrisporites* sp. The most important are common spores of *Densoisporites nejburgii* (Schulz) Balme. Phytoplankton is represented by single specimens of *Tasmanites* sp. and *Micrhystridium* sp. Species *D. nejburgii* and *L. pellucidus* were chosen for the designation of this assemblage. It is assumed that the assemblage corresponds to the end of the Early and the beginning of the Middle Triassic. This correlation is based on the presence of taxa known from assemblages of both the Lower and Middle Triassic deposits (Balme, 1970; Orłowska-Zwolinska, 1984; Reitz, 1985; Eshet and Cousminer, 1986).

The assemblage with *Rewanispora vermiculata–Voltziaceaesporites heteromorpha* (II) was recorded in the "Mulussa" Formation in the Wahab-1 well (interval 1791 - 1795 m). Like the previous one, this assemblage

Plate II.

1 – *Kyrtomisporis corrugatus* Cameron, 1974, Maaza-1, 2871.5 m. 2 – *Stellapollenites thiergartii* (Mädler) Clement-Westerhof *et al.*, 1974, Afandi-1, int. 2178 - 2184 m. 3 – *Retitriletes* sp. A, Van de Eem, 1983, Afandi-1, int. 2184 - 2190 m. 4 – cf. *Rimaesporites aquilonalis* Goubin, 1965, Maaza-1, 2871.5 m. 5 – *Rimaesporites* sp., Abba-1, int. 1873 - 1875 m. 6 – *Heliosaccus dimorphus* Mädler, 1964, Afandi-1, int. 2178 - 2184 m. 7 – *Duplicisporites granulatus* (Leschik) Scheuring, 1970, Abba-1, int. 1893 - 1896 m. 8 – *Camerosporites secatus* (Leschik) Scheuring, 1970, Habari-1, int. 1312 - 1327 m. 9 – *Accinctisporites* sp., Wahab-1, int. 2010 - 2040 m. 10 – *Lunatisporites pellucidus* (Goubin) Helby, 1972, Wahab-1, int. 2010 - 2040 m. 11 – *Samaropollenites speciosus* Goubin, 1965, Rumelan-6, int. 2504 - 2524 m. 12 – *Elongatosaccites triassicus* Cameron, 1974, Maaza-1, 2871 m. ×500 for 4, 12; ×750 for 9, 11; ×1000 for 1 - 3, 5 - 8, and 10.

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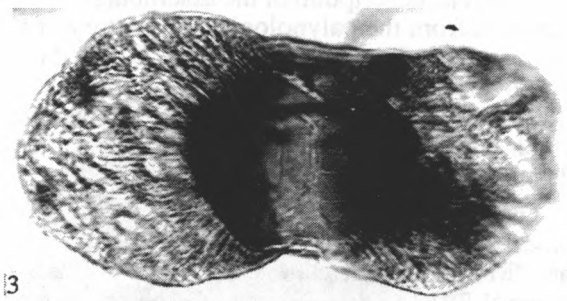
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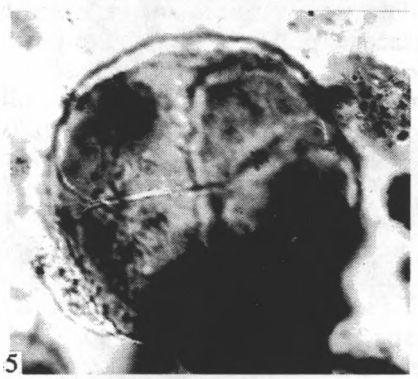
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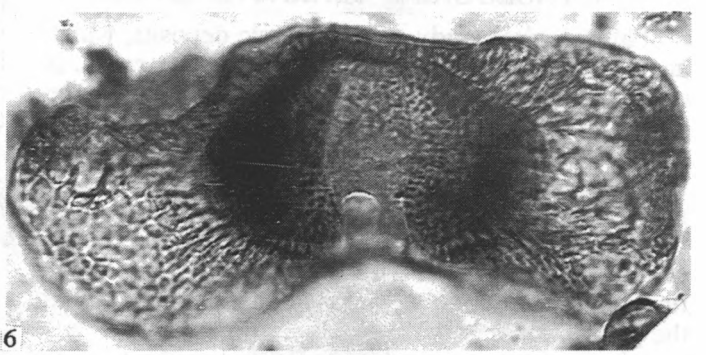
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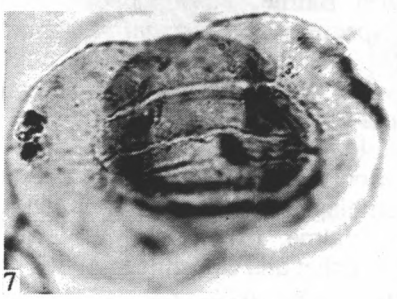
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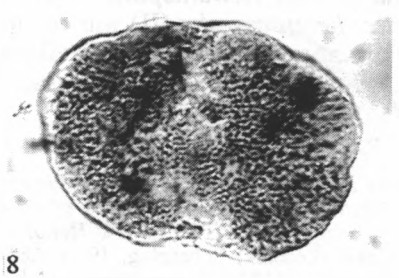
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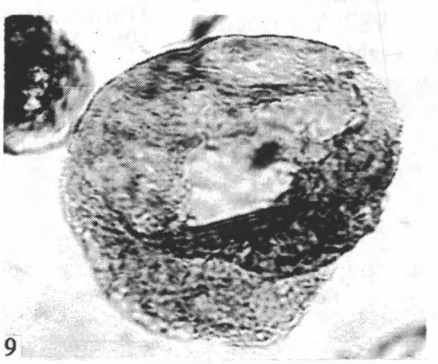
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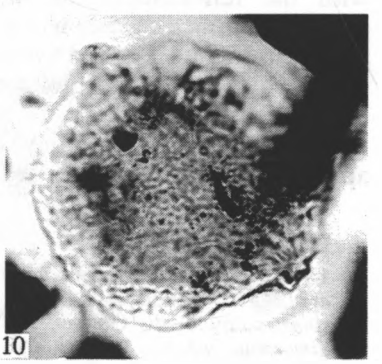
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Plate III.

is not diverse. It is also dominated by pollen of *Alisporites* spp., *Triadispora* spp., *Angustisulcites* sp., and *Lunatisporites* spp. Pollen of *Microcachrydites* cf. *doubingeri* Klaus, *Striatoabietites aytugii* Visscher, and *Stellapollenites* cf. *thiergartii* occurs as single grains. Pollen grains of *Voltziaceaesporites heteromorpha* Klaus are more numerous. As in the preceding assemblage, the taxonomic diversity of the spores is also low. In contrast, a marked increase in *Aratrisporites* spp. is observed. Phytoplankton is represented only by *Leiosphaeridia* sp. The presence of spores *Rewanispora vermiculata* Ant. et Taug.-Lantz as well as single poorly preserved specimens of *Perotrilites minor* (Mädler) Ant. et Taug.-Lantz is significant for the assemblage. The typical taxa chosen for the designation of this assemblage, *R. vermiculata* and *V. heteromorpha*, appear at this level in considerable quantities. *R. vermiculata* and *P. minor* are typical for the Anisian deposits of Romania, which are dated by ammonite fauna (Antonescu, 1970; Antonescu and Taugourdeau-Lantz, 1973). Finds of *P. minor* are also recorded in the Anisian assemblages of the western Caucasus (Yaroshenko, 1978) and in the lower part of the Muschelkalk of Germany (Reitz, 1985). The other typical species, *V. heteromorpha*, is known from European sequences in both the upper part of the Lower Triassic (Klaus, 1964; Visscher and Brugman, 1981; Reitz, 1985) and the Middle Triassic, particularly in the Anisian (Yaroshenko, 1978; Orłowska-Zwolinska, 1984; Adloff *et al.*, 1986). This taxon, together with *Alisporites grouvogeli,* was used to establish the lower Anisian zone in Israel (Eshet and Cousminer, 1986). Thus, the considered assemblage may be correlated with the Anisian, probably with its lower or middle part.

The ages of assemblages I and II, based on sparse records, are determined very tentatively.

The assemblage with *Stellapollenites thiergartii–Heliosaccus dimorphus* (III) was studied in six samples from the Kurachine Formation deposits in the Afandi-1 (intervals 2160 - 2166 m, 2178 - 2184 m, and 2184 - 2190 m) and Abba-1 (intervals 2119 - 2121 m, 2166 - 2181 m, and 2193 - 2214 m) wells. The miospore assemblage differs from the two previous and all the following ones in its maximum abundance and diversity of the ribbed pollen *Lunatisporites noviaulensis* var. *mollis* Scheuring, *L. acutus* (Leschik) Scheuring, *Lunatisporites* sp., and *Striatites* spp. Its diversity increases due to the appearance of species either restricted only to these layers, such as *Dyupetalum* sp. and *Heliosaccus dimorphus* Mädler, or forms that are also recorded in the upper Ladinian, such as *Uvaesporites gadensis* Praehauser-Enzenberg, *Keuperisporites baculatus* Schulz, *Microreticulatisporites galli* Adloff et Doubinger, *Triplexisporites playfordii* (de Jersey et Hamilton) Foster, and *Staurosaccites quadrifidus* Dolby.

Species *Doubingerispora filamentosa* Scheuring and *Kuglerina meieri* Scheuring, *Podocarpidites keuperianus* (Mädler) Schuurman occur even higher, in the Carnian. The newly appearing species apparently include cf. *Rimaesporites aquilonalis* Goubin. This form occurs also in younger deposits, and it is particularly abundant in the Norian assemblage (the Maaza-1 well).

The assemblage is named after the characteristic taxa *Stellapollenites thiergartii* and *Heliosaccus dimorphus* and dated as the late Anisian - early Ladinian. The transitional position of the assemblage is established on the basis of the presence of species typical for both of the stages. The first taxon is abundant here, though its scarce and poorly preserved specimens are also recorded in older deposits. The species *S. thiergartii* is stratigraphically significant for the upper Anisian of Alpine facies (Visscher and Brugman, 1981). This species was used to designate the late Anisian phase in the western Dolomite Alps of Italy (Van der Eem, 1983), though its finds are known in older deposits, for example, in the upper part of the Buntsandstein of the German basin (Reitz, 1985). The distribution of the other typical species, *H. dimorphus,* is restricted to the Ladinian in Alpine sequences. It is noteworthy that this species co-occurs with *Keuperisporites baculatus* both in the considered assemblage and in the Anisian and Ladinian assemblages of Libya (Adloff *et al.*, 1986). Both species *H. dimorphus* and *K. baculatus* were found in the lower Keuper of Germany (Reitz, 1985), and the latter form was also reported from the middle part of the Anisian in France (Doubinger and Adloff, 1981). Two species of protomonosaccate pollen *Kuglerina meieri* and *Doubingerispora filamentosa* are known from the upper Ladinian in the sequences of the Southern Alps (Scheuring, 1978). In Germany they are known from the middle Muschelkalk (Reitz, 1985). In sequences of the Dolomite Alps, *K. meieri* together with *Triplexisporites playfordii* and *Uvaesporites gadensis* have a wider stratigraphic range from the uppermost Anisian to the Carnian, which is supported by our data. Pollen of *Triadispora*, typical for many Middle Triassic sections, constantly occurs in the assemblage in a normal abundance. Apart from the taxa cited above, there are also some forms known from the older assemblages: *Aratrisporites* sp., *Densoisporites nejburgii, Microcachryidites* cf. *doubingeri, Platysaccus queenslandi, Voltziaceaesporites heteromorpha,*

Plate III.

1 – *Vesicaspora schemeli* Klaus, 1963, Maaza-1, 2871.5 m. 2 – *Voltziaceaesporites heteromorpha* Klaus, 1964, Abba-1, int. 1893 - 1896 m. 3 – *Platysaccus queenslandi* de Jersey, 1962, Afandi-1, int. 2184 - 2190 m. 4 – *Lunatisporites noviaulensis mollis* Scheuring, 1970, Afandi-1, int. 2178 -2184 m. 5 – *Staurosaccites quadrifidus* Dolby, 1976, Abba-1, int. 1893 - 1896 m. 6 – *Podocarpidites keuperianus* (Mädler) Schuurman, 1977, Afandi-1, int. 2160 - 2166 m. 7 – *Lunatisporites acutus* (Leschik) Scheuring, 1970, Abba-1, int. 1873 - 1875 m. 8 – *Triadispora* sp., Afandi-1, int. 2178 - 2184 m. 9 – *Patinasporites densus* (Leschik) Scheuring, 1970, Abba-1, int. 1873 - 1875 m. 10 – *Enzonalasporites* sp., Maaza-1, 2868.7 m. ×500 for 1; ×1000 for 2 - 10.

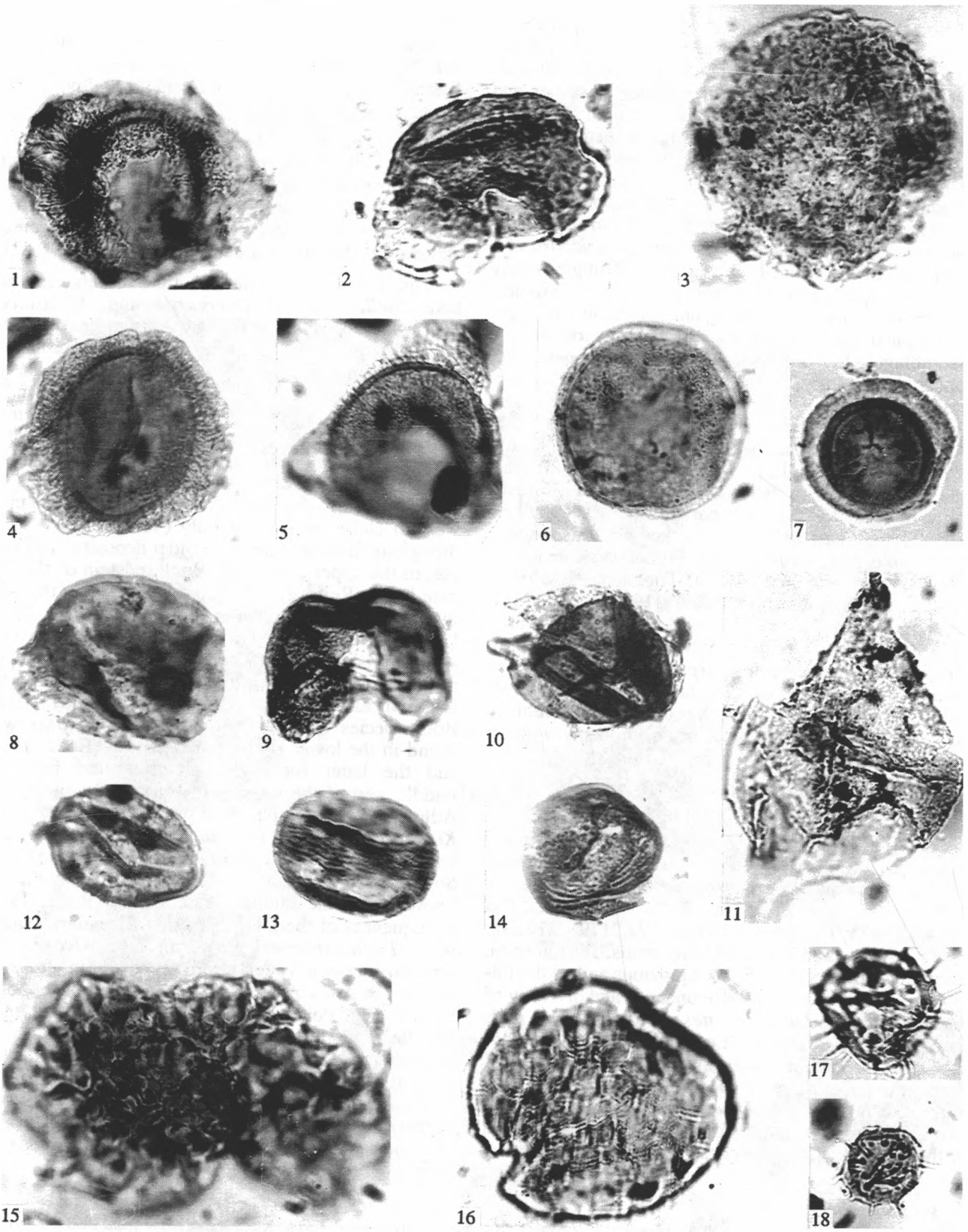


Plate IV.

and others. Phytoplankton is represented by the following forms: *Leiosphaeridia* sp., *Micrhystridium* sp., and *Cymatiosphaera* sp. They scarcely occur in the Afandi-1 well and are considerably more abundant in the Abba-1 well, which indicates more pronounced conditions of open marine sedimentation in the latter region, as compared to the former. The established association of miospores corresponds to that of the phase *Stellapollenites thiergartii–Dyupetalum vicentinense* from the upper Anisian deposits of the western Dolomite Alps in Italy (Van der Eem, 1983). The sole difference is the presence of the Ladinian pollen of *H. dimorphus* in the former association. The similarity of the two compared assemblages is stressed by the presence of the common forms of the genera *Stellapollenites, Dyupetalum, Staurosaccites, Lunatisporites, Triadispora, Kuglerina,* and *Uvaesporites* as well as *Ovalipollis pseudoalatus* and the group *Circumpolles*. The stratigraphic distribution of most miospores of the given assemblage is characteristic for the Middle Triassic of the stratotype area and the adjacent ones.

The assemblage with *Camerosporites secatus–Kuglerina meieri* (IV) was studied in three samples from the Kurachine (?) Formation in the Abba-1 well (intervals 1893 - 1896 m, 1912 - 1914 m, and 1914 - 1915 m). It retains many features of the previous assemblage. Specifically, many forms of the previous association continue to occur in the given one. These forms are *Lunatisporites acutus* (Leschik) Scheuring, *L. noviaulensis mollis* Scheuring, 1970, *Triadispora* spp., *Podocarpidites keuperianus* (Mädler) Schuurman, and *Protodiploxypinus gracilis* Scheuring. At the same time, other forms disappear, such as *Densoisporites nejburgii, Retitriletes* sp. A. Van der Eem, and others.

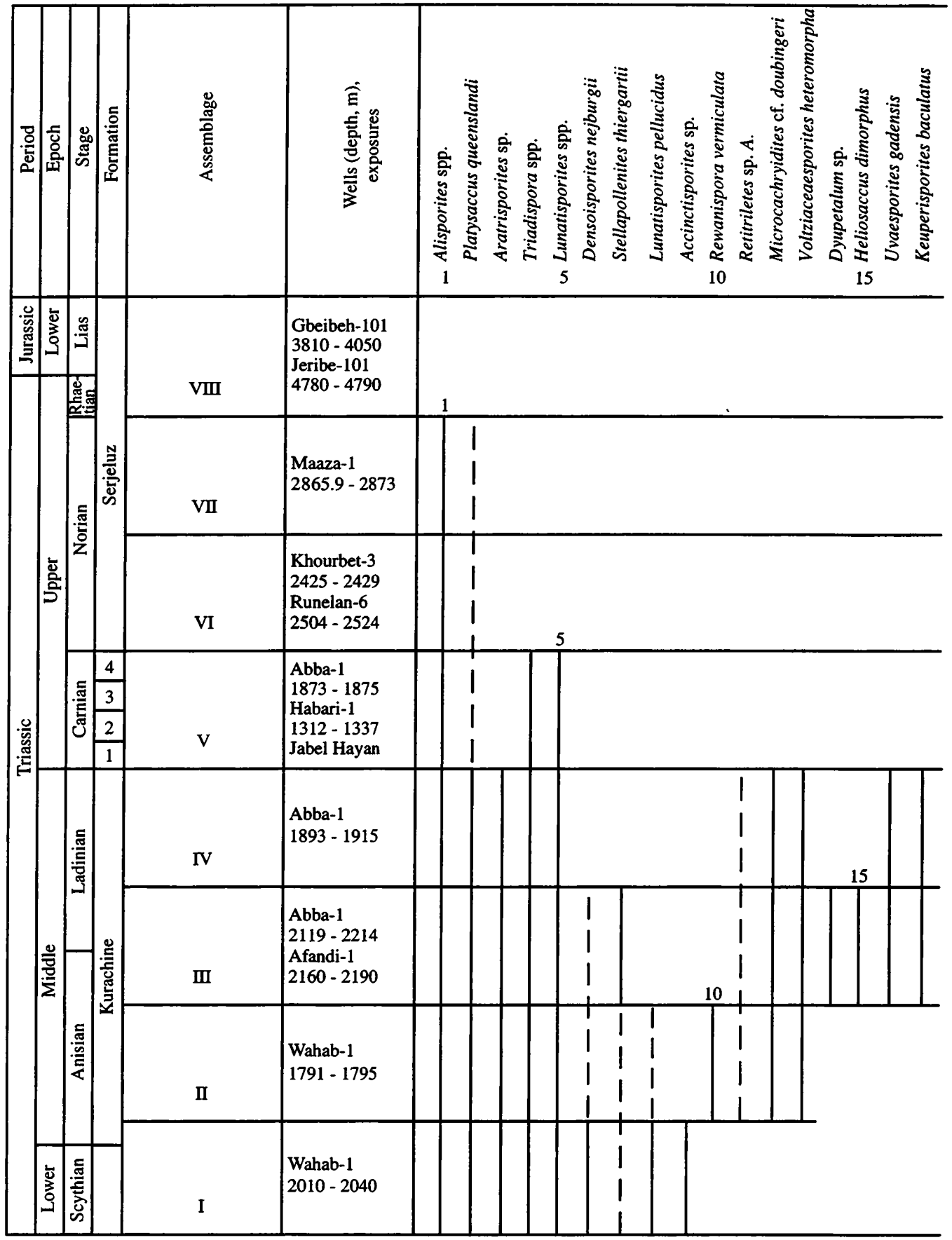
The main distinctive feature of the present assemblage is the appearance of pollen of the group *Circumpolles*. It is represented by its archaic elements, such as *Camerosporites secatus* (Leschik) Scheuring, *Paracirculina scurillis* Scheuring, and *Duplicisporites granulatus* (Leschik) Scheuring. These forms were previously considered as typical of the Late Triassic; their finds were attributed to post-Ladinian deposits. However, the study of palynoflora from the upper Ladinian deposits, in the Alpine sequence dated by macro- and microfauna, showed the presence of the mentioned taxa (Mostler and Scheuring, 1974). When compared with this palynoflora, the described assemblage shows common forms, such as *Circumpolles* group, *Uvaesporites gadensis, Aratrisporites* spp., *Triadispora* spp., and *Lunatisporites acutus*. The other important reference sequence is the Alpine section of the Meride Limestone in Switzerland (Scheuring, 1978). A number of forms, which are also typical for Syria, were extensively illustrated in this upper Ladinian assemblage: *Lunatisporites noviaulensis mollis, Protodiploxypinus gracilis, Triadispora* spp., *Kuglerina meieri,* and *Doubingerispora filamentosa*. Based on the appearance of *Camerosporites secatus* and common occurrence of the *Kuglerina meieri* pollen, the assemblage is designated by these taxa.

A comparison of the miospore composition of the described assemblage with that of the stratotypic Ladinian sequence of the Alps made it possible to correlate it with the Ladinian, apparently with its upper part. Based on the presence of *C. secatus* in association with typical forms of the phase of *C. secatus* comprising the Ladinian and Carnian (Besems, 1982, 1983; Van der Eem, 1983), the Syrian assemblage can be attributed to that phase too, but to its older (i.e., Ladinian) part. This agrees with the correlation of the given assemblage with that of the subphase *C. secatus–K. meieri,* which was established for the Ladinian of southern Spain (Besems, 1983). Features in common with the assemblage of this subphase are a high abundance of *Triadispora* spp. and the presence of *C. secatus, D. granulatus, Paracirculina scurrilis,* and *Kuglerina meieri*. Unlike the Spanish assemblage, the Syrian one shows abundant *Lunatisporites* spp. and an absence of *Ovalipollis*. This is a possible indication of the paleogeographic differences between the two regions. Some differences are also obvious in phytoplankton taxonomic composition. As compared to older ones, its quantity in the described assemblage increases. The group is represented by *Cymatiosphaera* sp. and *Micrhystridium* sp. Hence, the assemblage with *Camerosporites secatus–Kuglerina meieri* differs from the assemblage of *Stellapollenites thiergartii–Heliosaccus dimorphus* in the appearance of the pollen group *Circumpolles,* which reaches its maximum development in the Carnian.

The assemblage with *Patinasporites densus–Samaropollenites speciosus* (V) was established in the deposits of the Butmah (?) Formation in the Abba-1 well (interval 1873 - 1875 m) and in deposits with a the similar stratigraphic position in other parts of Syria (the "Mulussa" Formation in the Habari-1 well, interval

Plate IV.

1 – *Doubingerispora filamentosa* Scheuring, 1978, Afandi-1, int. 2160 - 2166 m. 2 – *Microcachrydites* cf. *doubingeri* Klaus, 1964, Abba-1, int. 2166 - 2181 m. 3 – *Vallasporites* sp., Habari-1, int. 1312 - 1327 m. 4 – *Kuglerina meieri* Scheuring, 1978, Afandi-1, int. 2184 - 2190 m. 5 – *Dyupetalum* sp., Afandi-1, int. 2178 -2184 m. 6 – *Praecirculina granifer* (Leschik) Klaus, 1960, Habari-1, int. 1312 - 1327 m. 7 – *Paracirculina tenebrosa* Scheuring, 1970, Habari-1, int. 1312 - 1327 m. 8 – *Minutosaccus crenulatus* Dolby, 1976, Rumelan-6, int. 2504 - 2524 m. 9 – *Protodiploxypinus gracilis* Scheuring, 1970, Abba-1, int. 1873 - 1875 m. 10 – *Perinopollenites elatoides* Couper, 1958, Gbeibeh-101, int. 4000 - 4025 m. 11 – *Rhaetogonyaulax rhaetica* (Sarjeant) Loeblich et Loeblich, 1968, Maaza-1, 2869.5 m. 12 – ? *Rhaetipollis* sp., Gbeibeh-101, int. 3810 - 3830 m. 13, 14 – *Classopollis* spp.: 13 – Maaza-1, 2868.7 m. and 14 – Gbeibeh-101, int. 3970 - 3990 m. 15 – *Botryococcus* sp., Maaza-1, 2867.9 m. 16 – *Cymatiosphaera* sp., Maaza-1, 2869.5 m. 17, 18 – *Micrhystridium* spp.: 17 – Maaza-1, 2869.5 m and 18 – Abba-1, int. 2166 - 2181 m. ×1000 for all figures.


Period
Epoch
Stage
Formation
Assemblage
Wells (depth, m), exposures
Alisporites spp.
Platysaccus queenslandi
Aratrisporites sp.
Triadispora spp.
Lunatisporites spp.
Densoisporites nejburgii
Stellapollenites thiergartii
Lunatisporites pellucidus
Accinctisporites sp.
Rewanispora vermiculata
Retitriletes sp. A.
Microcachryidites cf. doubingeri
Voltziaceaesporites heteromorpha
Dyupetalum sp.
Heliosaccus dimorphus
Uvaesporites gadensis
Keuperisporites baculatus
1
5
10
15
Triassic
Jurassic
Upper
Middle
Lower
Lias
Rhaetian
Norian
Carnian
Ladinian
Anisian
Scythian
Serjeluz
Kurachine
4
3
2
1
VIII
Gbeibeh-101
3810 - 4050
Jeribe-101
4780 - 4790
VII
Maaza-1
2865.9 - 2873
VI
Khourbet-3
2425 - 2429
Runelan-6
2504 - 2524
V
Abba-1
1873 - 1875
Habari-1
1312 - 1337
Jabel Hayan
IV
Abba-1
1893 - 1915
III
Abba-1
2119 - 2214
Afandi-1
2160 - 2190
II
Wahab-1
1791 - 1795
I
Wahab-1
2010 - 2040

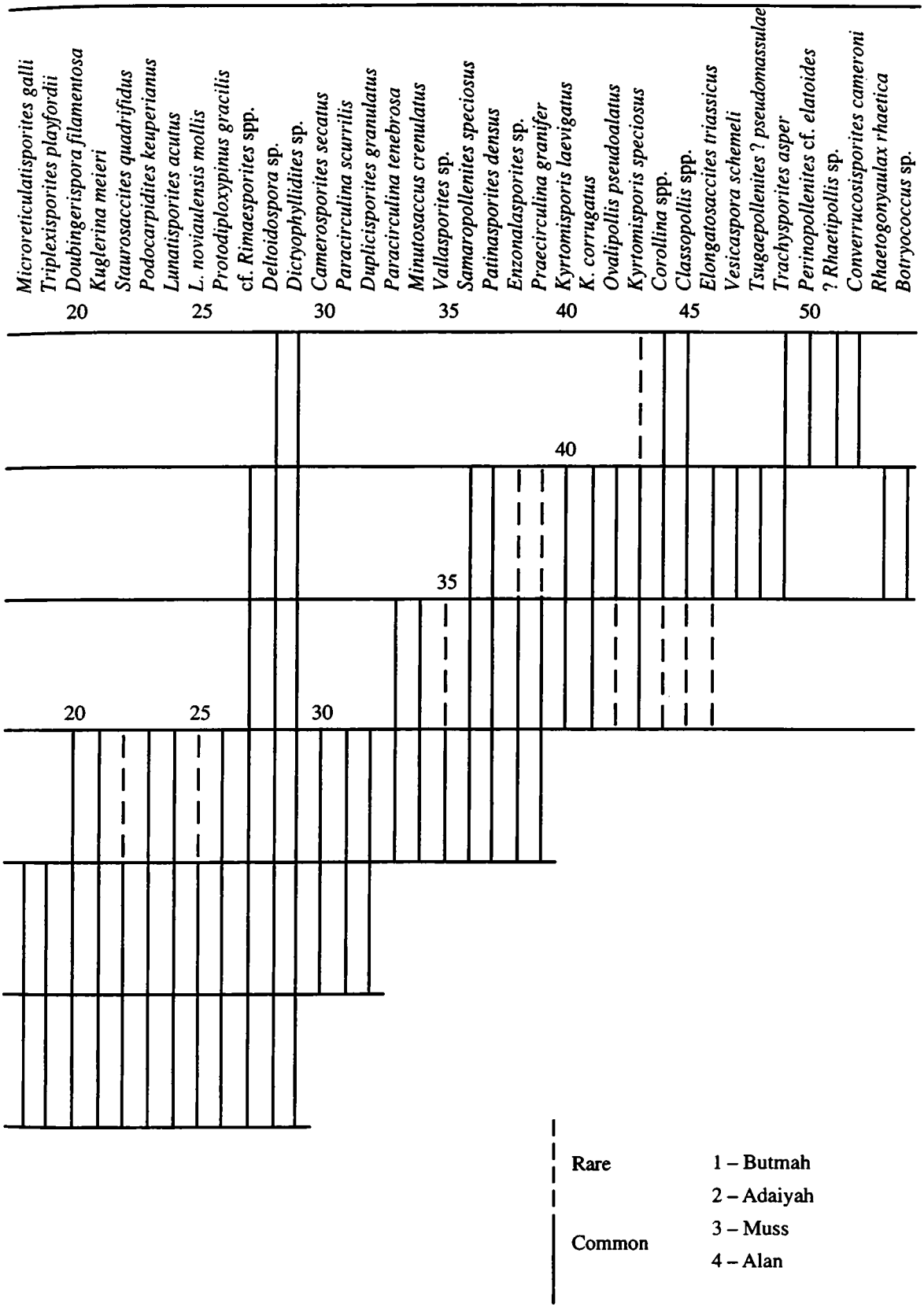


Fig. 2. Scheme of palynomorph distribution in the Middle and Upper Triassic deposits of Syria.
I - VIII – assemblages with characteristic taxa: I – *Densoisporites nejburgii–Lunatisporites pellucidus*; II – *Rewanispora vermiculata–Voltziaceaesporites heteromorpha*; III – *Stellapollenites thiergartii–Heliosaccus dimorhus*; IV – *Camerosporites secatus–Kuglerina meieri*; V – *Patinasporites densus–Samaropollenites speciosus*; VI – *Corollina meyeriana–Kyrtomisporis corrugatus*; VII – *Corollina meyeriana–Vesicaspora schemeli*; VIII – *Corollina meyeriana–Converrucosisporites cameroni*.

1312 - 1337 m). This assemblage differs from the above-described one in marked changes in the miospores composition. The content of pollen of *Triadispora* spp., *Lunatisporites* spp., *Kuglerina meieri, Doubingerispora filamentosa*, and *Staurosaccites quadrifidus* decreases, and many taxa that are typical of the previous assemblage disappear. The important feature of the assemblage is the mass occurrence of the *Circumpolles* group. The group had already appeared in moderate abundance in the Ladinian assemblage, which is separated from the considered one by an 18-m-thick interval in the Abba-1 well. *Paracirculina scurillis* in the Abba-1 well and *Camerosporites secatus* in the Habari-1 well are distinguished in the group with high abundances. In these wells, they are accompanied by *Duplicisporites granulatus* and *Paracirculina tenebrosa* Scheuring, which occur in common abundance. Apart from the mass occurrence of the pollen of *Circumpolles*, the appearance of the following is noteworthy: *Patinasporites densus* (Leschik) Scheuring, *Samaropollenites speciosus* Goubin, *Minutosaccus crenulatus* Dolby, *Enzonalosporites* sp., *Vallasporites* sp., *Paracirculina tenebrosa,* and *Praecirculina granifer* (Leschik) Klaus. These forms are significant for the age determination of the Carnian deposits. Two taxa deserve special consideration, because they are used for the designation of the described assemblage. Species *P. densus* and *S. speciosus* have wide geographic distributions. The European species *P. densus* was described from the middle Keuper in the German Facies of Switzerland (Scheuring, 1970). Later, it was studied together with *Circumpolles* forms in the upper Carnian of Alpine sequences in Sicily, which are dated by ammonites and conodonts (Visscher and Krystyn, 1978). This form was considered to be a reference species for the upper Carnian deposits of the Alps and their analogues in sequences in England (Fisher, 1972), the USA (Fisher and Dunay, 1984; Litwin, 1985), and Israel (Eshet and Cousminer, 1986). However, the study of sections of the Northern Calcareous Alps in Austria showed the presence of *P. densus* in the base of the *Trachyceras aon* Zone (Dunay and Fisher, 1978). In the sections of the Dolomite Alps in Italy, this species is accepted as one of the reference forms for two Phases established for deposits of the Cordevolian and Julian. The cooccurence of *P. densus* with *S. speciosus, Triadispora, Protodiploxypinus gracilis, Lunatisporites acutus, C. secatus, P. scurrilis,* and *P. tenebrosa* enabled this association to be correlated with assemblages from the Aziza I and II formations of Libya, which also correspond to the Carnian (Adloff *et al.*, 1986). A number of taxa make the considered assemblage similar to assemblages of the lower Gipskeuper of Germany (Reitz, 1985) and the Carnian of northeastern France (Geisler *et al.*, 1978).

The other species, *Samaropollenites speciosus*, is the Gondwana taxon. It is used for designating the Carnian zone in western Australia (Dolby and Balme, 1976). It co-occurs there with *C. secatus* and species of the genus *Enzonalosporites*. Distribution areas of the former and *S. speciosus* are somewhat different. Whereas *P. densus* occurs in Europe and North America (Cornet and Olsen, 1985; Litwin, 1985) and in Morocco (Cousminer and Monspeizer, 1976), finds of *S. speciosus* are mainly confined to Gondwana [Madagascar, western Australia, and India (Goubin, 1965; Maheshwari *et al.*, 1976; Dolby and Balme, 1976)] and the Mediterranean [Sicily (Visscher and Krystyn, 1978), Spain (Besems, 1982, 1983), Libya (Adloff *et al.*, 1986), Syria (Yaroshenko and Bash Imam, 1989), and Israel (Cirilli and Eshet, 1991)]. The occurrence pattern of *S. speciosus* confirms the phytogeographic model for distribution of this species in two latitudinal belts to the north and to the south of the paleoequator (Visscher and Van der Zwan, 1981). In terms of the coocurrence of this taxon with *Camerosporites secatus, Enzonalosporites sp., Staurosaccites quadrifidus,* cf. *Rimaesporites aquilonalis,* and *Minutosaccus crenulatus*, assemblage V resembles the microflora of Onslow, which is composed of Gondwanian and European elements. In general, the assemblage with *Patinasporites densus–Samaropollenites speciosus* apparently corresponds to the southern Spanish palynoflora of the *C. secatus–P. densus* subphase. This subphase correlates with the younger part of the *C. secatus* phase, which is attributed to the Carnian.

The considered assemblage also includes the spectrum of one of the five samples collected from the Jabel Hayan outcrop during a work excursion to the Palmirids. Thin clayey interlayers in the hypsum beds yielded the following miospores: *Camerosporites secatus, Duplicisporites granulatus, Paracirculina scurrilis,* and *P. tenebrosa. Patinasporites densus, Samaropollenites speciosus, Enzonalasporites* sp., *Vallasporites* sp., and *Triadispora* are less abundant. Specimens of *Lunatisporites* occur only sporadically. The species list shows that the miospore association of Jabel Hayan is similar to that of the Abba-1 (interval 1873 - 1875 m) and Habari-1 (interval 1312 - 1337 m) wells. This indicates a Late Triassic and, in all probability, a Carnian age. Though they are poorly preserved and especially colorless because of the great extent of weathering, the miospores were still rather reliably determined. Thus, the discovery of Late Triassic miospores in the Jabel Hayan section confirms the exposure of the Triassic rocks in Syria not only in the Bassit region, but also in the Palmirids.

The assemblage with *Corollina meyeriana–Kyrtomisporis corrugatus* (VI) was studied in the deposits of the Serjelu Formation in the Khurbet-3 (interval 2425 - 2429 m) and Rumelan-6 (interval 2504 - 2524 m) wells. In the composition of miospores, this assemblage considerably differs from the previous one. Many taxa disappear, including the ribbed pollen of *Lunatisporites* spp. and *Doubingerispora filamentosa, Kuglerina meieri, Camerosporites secatus,* and *Duplicisporites granulatus.* At the same time, the content of *Samaropollenites speciosus* notably increases. Some forms from the older assemblages continue to occur in

the considered one, stressing their close relations. These forms are *Patinasporites densus*, *Enzonalasporites* sp., *Vallasporites* sp., *Paracirculina tenebrosa*, *Triadispora* spp., *Protodiploxypinus gracilis*, *Minutosaccus crenulatus* Dolby, and cf. *Rimaesporites aquilonalis*.

The main distinction of the described assemblage is the appearance of the pollen *Corollina meyeriana* Klaus and *Corollina* sp and scarce specimens of *Granuloperculatipollis* sp. and *Classopollis* sp. The presence of these forms and the disappearance of *C. secatus* and *D. granulatus* indicate the replacement of old elements of the *Circumpolles* group with its younger members. At the same time, diverse spores of the genus *Kyrtomisporis* appear: *K. laevigatus* Mädler, *K. speciosus* Mädler, and *K. corrugatus* Cameron. Newly appearing *C. meyeriana* and *K. corrugatus* were chosen as characteristic taxa for the designation of the given assemblage. In addition, this association includes fragments of scarce specimens of *Elongatosaccites triassicus* Cameron. This species was described together with *Kyrtomisporis corrugatus* from Upper Triassic deposits that were penetrated by wells in Saudi Arabia and from the Baluti shales of Iraq (Cameron, 1974). The species *E. triassicus* is also known in the upper Carnian assemblage of Libya (Adloff *et al.*, 1986). The appearance of *Corollina meyeriana* and the absence of *Camerosporites* and *Duplicisporites* are usually regarded as the characteristic features of the post–Carnian assemblages. The given assemblage resembles the association from southeastern Spain (Besems, 1982). This association was assigned to the late Norian on the basis of its correlation with phase 2 (Schuurman, 1977, 1979), which was marked by the appearance of rare *Corollina* and *Classopollis* and the disappearance of *C. secatus* and *D. granulatus*. Taking into account this data, we correlated the deposits containing the assemblage of *Corollina meyeriana–Kyrtomisporis corrugatus* with the Norian, which was problematic in this region earlier.

The assemblage with *Corollina meyeriana–Vesicaspora schemeli* (VII) was discovered in eight samples from the Serjelu Formation in the Maaza-1 well (depths of 2865.9, 2866.5, 2867.9, 2868.7, 2869.5, 2871, 2871.5, and 2873 m). The assemblage is distinct in that the taxonomic composition changes considerably. As in the previous assemblage, no ribbed forms were recorded. Members of the genus *Triadispora*, known in the preceding associations, disappear from the present one. Similar to the older assemblage, a gradual decrease in the archaic members of the *Circumpolles* group is observed. The distinctive feature of the given assemblage is a high abundance of *Corollina* and *Classopollis* species, which reach up to half of the total miospore content, whereas they were less abundant in the previous assemblage. Association VII is also distinct in the appearance of great amounts of *Vesicaspora schemeli* Klaus. Its presence, together with the constant occurrence of *Corollina meyeriana*, provides grounds for designating the described assemblage by these taxa.

This assemblage is also distinct in the appearance of *Tsugaepollenites* ? *pseudomassulae* Mädler and dinoflagellate *Rhaetogonyaulax rhaetica* (Sarjeant) Loeblich et Loeblich. It has some taxa in common with the previous assemblage: *Kyrtomisporis corrugatus*, *K. laevigatus*, and *K. speciosus* as well as *Enzonalosporites* sp., *Patinasporites densus*, and *Elongatosaccites triassicus*. Scarcely represented in the previous assemblage, the pollen of *Ovalipollis* spp. shows a marked increase in diversity here. The Gondwanian cf. *Rimaesporites aquilonalis* reaches its maximum abundance, comprising up to the half of the overall miospore content in some samples. The stratigraphic range of this species (from the Anisian to Norian) is rather wide, being similar to that in Australia (Dolby and Balme, 1976). Triangular and rounded smooth spores of *Deltoidospora*, *Dictyophyllidites*, *Concavisporites*, and *Todisporites* genera occur in considerably higher abundances in the present assemblage; isolated specimens of the *Duplexisporites* genus are observed too. The mass occurrence of *Vesicaspora schemeli* and common *Kyrtomisporis* species in association with *E. triassicus* facilitate a tentative correlation of the Serjelu Formation with the Upper Triassic deposits of Saudi Arabia and Iraq, from which several taxa, including the above-mentioned species, were described (Cameron, 1974). In general, it is hard to find a comparable assemblage; however, many taxa of the considered association are known from post-Carnian deposits. Similar assemblages are recorded from the Norian–Rhaetian and Rhaetian deposits of England (Fisher, 1972; Warrington, 1978), Germany (Brenner, 1986), and Austria (Morbey, 1975); Norian–Rhaetian deposits of northeastern Spain (Baudelot and Taugourdeau-Lantz, 1986); and Norian deposits of arctic Canada (Fisher and Bujak, 1975; Fisher, 1979). Apart from miospores, all these assemblages include dinoflagellates *Rhaetogonyaulax rhaetica*, which are typical of the Syrian assemblage too. However, contrary to most of the compared associations, the Syrian one lacks *Rhaetipollis germanicus* Schulz and other reference forms of the Rhaetian. It is obvious that there is some resemblance to the assemblage of phase 2, which was conditionally established for the Norian deposits of the Calcareous Alps, Austria, and Germany as well as the associations of northeastern France and southern Luxembourg (Schuurman, 1977, 1979). Their similarity to the assemblage of phase 2 is based on finds of *Patinasporites densus*, *Paracirculina tenebrosa*, *Ovalipollis* sp., *Corollina* spp., *Classopollis* sp., and *Kyrtomisporis* spp. as well as the extreme decrease in or complete disappearance of *Triadispora* spp., *Camerosporites secatus*, and *Duplicisporites granulatus*. A number of common features enable the Syrian assemblage to be correlated with assemblage A2 of Portugal, which was first dated as the Carnian–Norian (Adloff *et al.*, 1974) and later as the Norian, as well as with the Norian palynoflora of Libya (Adloff *et al.*, 1986), which is distinct in its abundance of *Classopollis* pollen. In addition, the studied assemblage differs

from most compared palynofloras in high abundances of large, strongly elongated pollen of *Vesicaspora schemeli* and protodisaccate cf. *Rimaesporites aquilonalis*. Based on the correlation with the above-mentioned data, the palynoflora from the Maaza-1 well is assumed to be the Norian in age.

Accepting the Norian age for the last two assemblages with *Corollina meyeriana–Kyrtomisporis corrugatus* and *Corollina meyeriana–Vesicaspora schemeli*, respectively, it is worth noting that the first one is closely related to the Carnian assemblage and, representing a transition to the second one, may be considered as the early Norian. The second assemblage should then be referred to the late Norian. This is indicated by the numerous *Classopollis* spp. and finds of dinoflagellate *Rhaetogonyaulax* cf. *rhaetica*. Though the latter form is typical for the whole Rhaetian, it is also recorded in the Norian deposits of arctic Canada (Fisher and Bujak, 1975). The occurrence of dinoflagellates along with the high abundance of *Botryococcus* sp. and less common forms of *Cymatiosphaera* indicate the onset of more open marine conditions in the region. In general, both assemblages have some features that are similar to those of the Norian assemblages of the Mediterranean (Algeria, Libya, and Portugal), including Syria. All these associations display numerous pollen of *Corollina, Classopollis*; a presence of uniform spores; a constant record of Ovalipollis; and, significantly, an absence of *Rhaetipollis germanicus* Schulz, *Ricciisporites, Triancoraesporites, Zebrasporites,* and other Rhaetian taxa typical of the north European assemblages.

The assemblage with *Corollina meyeriana–Converrucosisporites cameroni* (VIII) was studied in five samples from the Serjelu Formation, which was penetrated by two wells: Gbeibeh-101 (intervals 3810 - 3830, 3970 - 3990, 4000 - 4025, and 4030 - 4050 m) and Jeribe-101 (interval 4780 - 4790 m). This assemblage sharply differs from assemblage VII and all the previous ones in its impoverished composition. It is largely dominated by the pollen of *Corollina*; species of the *Classopollis* genus occur in common abundances. Among the spores, triangular smooth forms of the *Dictyophyllidites* and *Concavisporites* genera as well as slightly ornamented *Converrucosisporites cameroni* (de Jersey) Playford et Dettmann show maximum abundances. Other taxa are represented by *Inaperturopollenites* sp. and single specimens of *Ovalipollis* sp., *Vitreisporites* sp., *Cycadopites* sp., *Kyrtomisporis speciosus*, *Trachysporites asper* Nilsson, and *Perinopollenites* cf. *elatoides* Couper. The name of the assemblage was preliminarily chosen on the basis of the mass occurrence of *C. meieriana* and the common presence of *C. cameroni*. The characteristic feature of this assemblage is the disappearance of taxa that were typical of the previous one and the complete absence of any disaccate pollen.

The mentioned miospores, occuring in both the Upper Triassic and the Lower Jurassic deposits (Lund, 1977; Pedersen and Lund, 1980; Brenner, 1986), when the reference taxa of the Rhaetian and Lias are absent, make it possible to consider this assemblage as the transitional Rhaetian–Lias one. Here, some problematic fragmentary finds should be noted. They include folded forms resembling isolated hemispheres of *Rhaetipollis germanicus* Schulz lacking its typical verrucae. We conditionally named these forms ? *Rhaetipollis* sp. (Plate IV, Fig. 12). Finds of true *R. germanicus* in association with the known taxa, which are typical for the Rhaetian, may serve as a basis for the correlation of our assemblage with the Rhaetian. However, there is evidence that, unlike the European record, in the assemblages of the terminal Triassic in the sequences along the southern margin of the Tethys there are no finds of *R. germanicus* and other reference species of the Rhaetian (Adloff *et al.*, 1986). Thus, additional material is still required for the age determination of the described assemblage in order to unequivocally chose between the Rhaetian and Lias or to confirm the transitional Late Triassic - Early Jurassic age, which is assumed in the present work.

DISCUSSION

Palynological data are a rather reliable instrument for the subdivision of Triassic deposits. However, their use in the interpretation of climatic conditions and facies environments still remains limited. However, notable progress has been made during the last decade due to the appearance of numerous works (Visscher and Van der Zwan, 1981; Besems, 1982, 1983; Van der Eem, 1983; Reitz, 1985; Duringer and Doubinger, 1985; Adloff *et al.*, 1986; Eshet and Cousminer, 1986; and others).

The taxonomic dynamics of miospores at various chronological levels of the Middle and Late Triassic reflects certain stages in the evolutionary development of palynoflora that are undoubtedly related to environmental changes. In the studied region, the tentatively outlined stages in the Ladinian and Norian reflect, in all probability, the general transformation of the Triassic vegetation of Eurasia, which was recorded by both macrofloral (Dobruskina, 1982) and palynological materials (Yaroshenko, 1993).

Carbonate and evaporite deposits of northeastern and central Syria show extensive development of marine, shallow marine, and lagoon facies. This resulted in a certain regularity in the distribution of palynomorph groups, which, along with some types of rocks, can serve as indicators of climate and sedimentary environments.

The compositions of the assemblages show a clear predominance of disaccate pollen, particularly ribbed *Lunatisporites* spp. in the Anisian and Ladinian, monosaccate pollen of *Stellapollenites thiergartii* in the uppermost Anisian - lowermost Ladinian, and that of *Triadispora* spp. in the uppermost Ladinian. It is a well-

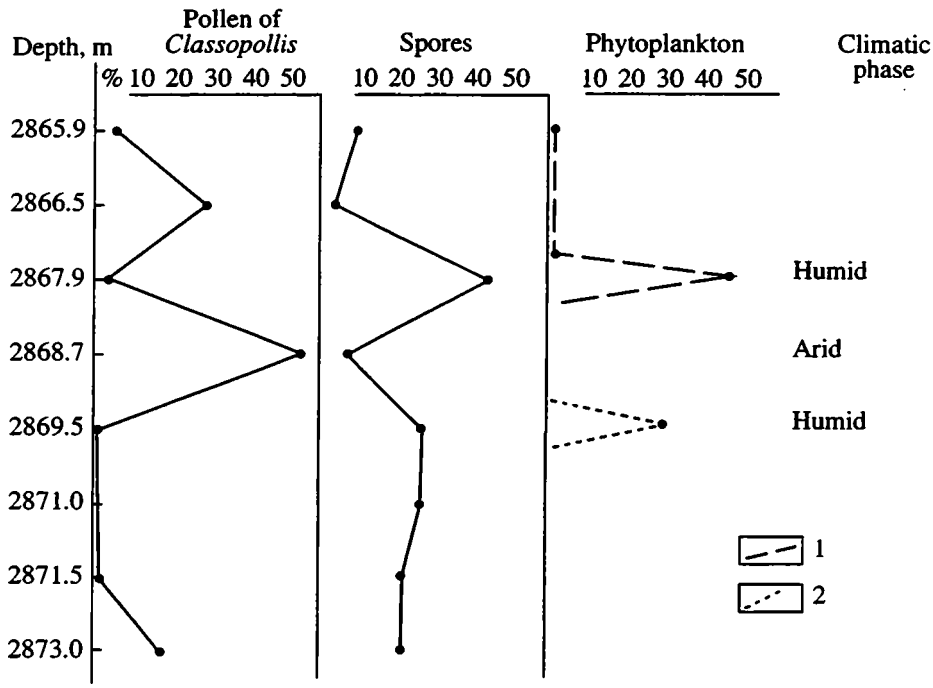


Fig. 3. Ratio of xerophytic and hydrophytic palynomorphs in the Norian (Maaza-1 well).
1 – *Botryococcus* and 2 – *Rhaetogonyaulax rhaetica.*

known fact that pollen of this type can be dispersed to great distances from the location of the mother plants; they can also be accumulated in both shallow marine and more open marine conditions, which is also confirmed by the occurrence of acritarchs. Representatives of this pollen group are thought to be xerophytic, and they are considered to be indicators of arid and semiarid climates (Visscher and Van der Zwan, 1981). Hydrophytic elements, such as spores of pteridophytes, are less adaptable to such environments, which is evident from the fact that their content is considerably lower than that of pollen.

By the end of the Ladinian, existing assemblages of disaccate ribbed pollen and forms of *Triadispora* were joined by asaccate pollen of the *Circumpolles* group. The group was not yet very numerous and included its more primitive genera *Camerosporites, Duplicisporites,* and *Paracirculina.* The flourishment of this group corresponds to the Carnian, when numerous new taxa appeared, whereas the share of spores and acritarchs sharply decreased. These features and, in particular, the abundance of asaccate pollen, which, owing to its morphology, is not easily transported and accumulates near the source plants, suggest the proximity of the coast and the existence of shallow marine basins, evaporite lagoons, and sebkhas. A similar situation, which reflects regressive sedimentary conditions, was demonstrated for the Carnian of the Negev area (Eshet and Cousminer, 1986).

In the post-Carnian time, a new restructuring of palynoflora is observed: older elements of the *Circumpolles* group were replaced by younger ones dominated by forms of *Corollina* and *Classopollis.* The predominance of the latter form, which was produced by xerophilous cheirolepidian plants, along with the high abundance of disaccate unribbed and monasaccate pollen apparently indicate climatic aridization also (Vakhrameev, 1980). The appearance of dinoflagellates, the presence of numerous *Botryococcus*, and the increased amount of pteridophyte spores imply the onset of marine conditions. This reflects the general humidization of the climate in the Latest Triassic to Earliest Jurassic. The Rhaetian and Lias palynoflora contains forms of miospores typical of the Late Triassic and Early Jurassic and may be regarded as transitional.

Thus, the palynological assemblages include mainly xerophytic elements: 75 - 98% in the Middle Triassic, 95 - 96% in the Carnian, 58 - 95% in the Norian, and 42 - 87% in the Rhaetian and Lias. The role of hydrophytic elements was suppressed. This indicates the extensive development of arid or semiarid environments in the territory of Syria during the Middle and Late Triassic.

A comparison of the Middle Triassic assemblages of the considered area with associations of the Italian Dolomite Alps (Van der Eem, 1983) shows a similar predominance of xerophytic elements along with some local variations. The Carnian palynological assemblage is close to palynofloras of the adjacent Negev area (Eshet and Cousminer, 1986) and southern Spain (Visscher and Van der Zwan, 1981; Besems, 1983). Red and evaporite deposits of the latter region serve as a basis

for considering it to be one of the most arid areas in the western Tethys during that time (Besems, 1983). In southeastern France, the existence of an arid climate from the middle Anisian through the Carnian is deduced from the distribution of morphological types of miospores (Taurgoudeau-Lantz, 1984).

Against the background of an arid climate, arid phases alternated with relatively more humid ones. This alternation reflects both transgressive–regressive events and climatic oscillations. This is confirmed by the changing ratio of xerophytic and hydrophytic elements. Changes in the composition of the Norian palynoflora in the Maaza-1 well may serve as an example (Fig. 3). In the depth interval 2873 - 2869.5 m, an increase in hydrophyte content occurs along with a notable decrease in the share of *Classopollis*, which indicates more humid environments related to the proximity of lagoons, gulfs, and other water basins. The appearance of abundant dinoflagellates at a depth of 2869.5 m clearly shows the onset of marine environments, which is indirectly confirmed by the reduction in *Classopollis* content. Higher in the sequence (2867.7 m), where dinoflagellates disappear and spore content notably decreases, the mass occurrence of the *Classopollis* pollen is recorded. The latter implies both increasing aridization (Vakhrameev, 1980) and the spread of xerophytic cheirolepidian plants in coastal areas, which were drained as a result of a regression. Still higher in the same sequence, at a depth of 2867.9 m, a domination of algae *Botryococcus*, a sharp decrease in *Classopollis* pollen content, and a higher abundance of spores are observed, which evidence a new transgression. *Botryococcus* algae are characteristic of the freshwater and slightly brackish-water deposits of the Carnian of Libya (Adloff *et al.*, 1986) and the Jurassic of Sweden (Guy-Ohlson, 1992). They are also characteristic of the Rhaetian brackish-water facies of the German basin (Lund, 1977; Brenner, 1986).

Taking into account the xerophytic composition of the Middle and Late Triassic palynofloras of Syria and their resemblance to the contemporaneous assemblages of the Mediterranean belt of the arid Equatorial province, we can confidently attribute the studied area to this belt.

CONCLUSION

Analysis of the palynological data from the Middle and Upper Triassic made it possible to recognize a succession of eight miospore assemblages, which serve as a basis for establishing corresponding units in the uppermost Lower - lowermost Middle Triassic through the Rhaetian–Liasic deposits.

Changes in the taxonomic composition of miospores at various chronological levels of the Middle and Late Triassic reflect certain stages in palynoflora evolutionary development, which are closely related to changes in the environments.

Against the background of sequential changes in palynolgical assemblages, a significant transformation of flora occured in the Ladinian and Norian. This resulted in the formation of a new type of miospore association, which further evolved during the terminal Triassic and Early Jurassic. Carbonate and evaporite deposits indicate the extensive development of marine, shallow marine, and lagoon facies, which resulted in certain regularities in the distribution of some miospores groups. This, along with lithologic features, serves as an indicator of the climate and sedimentary environments.

The xerophytic appearance of palynofloras of the Middle and Late Triassic of Syria and their similarity to synchronous assemblages of areas from the Mediterranean belt of the arid Equatorial province testify that the studied region belongs to this belt.

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Zoogeography of the Early Miocene Basins of Western Eurasia according to Bivalve Mollusks

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Abstract – Early Miocene warming caused fauna migrations from south to north. Mollusks, which previously inhabited only the Mediterranean Tethys, became widespread throughout the region under consideration. This integration of fauna resulted in the disappearance of the North European zoogeographic subregion, which had been traceable since the Mesozoic. According to the composition of their bivalve assemblages, the zoogeographic provinces of Germany and the central and eastern Paratethys were integrated into the Mediterranean subregion of the Tethys.

Key words: *Biogeography, Neogene, bivalve mollusks, Tethys, and Paratethys.*

Two important events that determined the future evolution of coastal fauna of marine mollusks are confined to the beginning of the Miocene: (1) the initiation of global warming reversed the primary direction of molluscan migrations, which was from north to south during the Oligocene, and (2) the basin of northwestern Europe, which had considerable influence on molluscan fauna during the Oligocene, lost its epicontinental connections with other European basins. Both events caused a considerable reorganization of molluscan assemblages in the basins of Central Europe and, especially, in the eastern Paratethys. These changes were completely manifested during the Burdigalian time, and between the Oligocene and the Burdigalian the Aquitanian bivalves had a transitional character everywhere. Difficulties in dating the assemblages put forward problems of detailed stratification, and the respective interval was considered as Aquitanian–Burdigalian. Nevertheless, the available data mainly reflect the distribution of bivalves typical of the Burdigalian, because assemblages of this age are significantly more abundant and widespread, especially in southern Europe. The transgressive character of the lower Miocene sediments, rich in sandy facies, and the warm-water character and diversity of the assemblages supported rather complete data on the composition of bivalves typical of this interval.

The analytical method was described in the first article of this series (Popov, 1994). The past revision of the composition of bivalve mollusks, using collections and published materials (Popov *et al.*, 1993), provided a basis for completing lists of bivalve species for different regions (paleobasins and their areas) of western Eurasia. The lists were used to analyze zoogeographical distribution and to reconstruct areals of characteristic genera and species.

However, the high diversity of Miocene fauna makes these lists too large for publication. For this reason, Table 2 shows only the distribution of genera and subgenera; the number of species present in the assemblages are indicated.

DESCRIPTION OF ASSEMBLAGES

Northern Africa. Lower Miocene bivalves are known in Algeria (Freneix *et al.*, 1974). This assemblage is not very diverse (there are 30 species of 24 genera and subgenera), but it is rather significant. It is undoubtedly a warm-water assemblage, but there are no tropical genera except for *Trisidos*. There were not many endemic species marked in this assemblage. Miocene and Oligocene species of Tethys origin that became widespread throughout the studied region at the beginning of the Miocene and species that first appeared in the lower Miocene and became widespread in the middle Miocene (*Anadara turonica, Gonimyrtea michelottii, Megaxinus transversus, Clausinella basteroti*, and *Dosinia lupinus*) are dominant. With the exception of the endemic forms, all species of this assemblage are identical to those of the extremely rich molluscan assemblage from the Aquitania, and many of them correspond to bivalves of Portugal (Fig. 1).

Southern Europe. Data for northern Italy are based both on old studies (Sacco, 1889 - 1904; Accordi, 1955; Piccoli *et al.*, 1977), in which many datings are doubtful, and on species distributions analyzed for other Mediterranean regions. These data need further improvement. Despite the higher proportions of endemics (13%) among Italian bivalves, species and genera of wide geographical distribution (group III in Table 2) and those common to central European basins (group II) predominate.

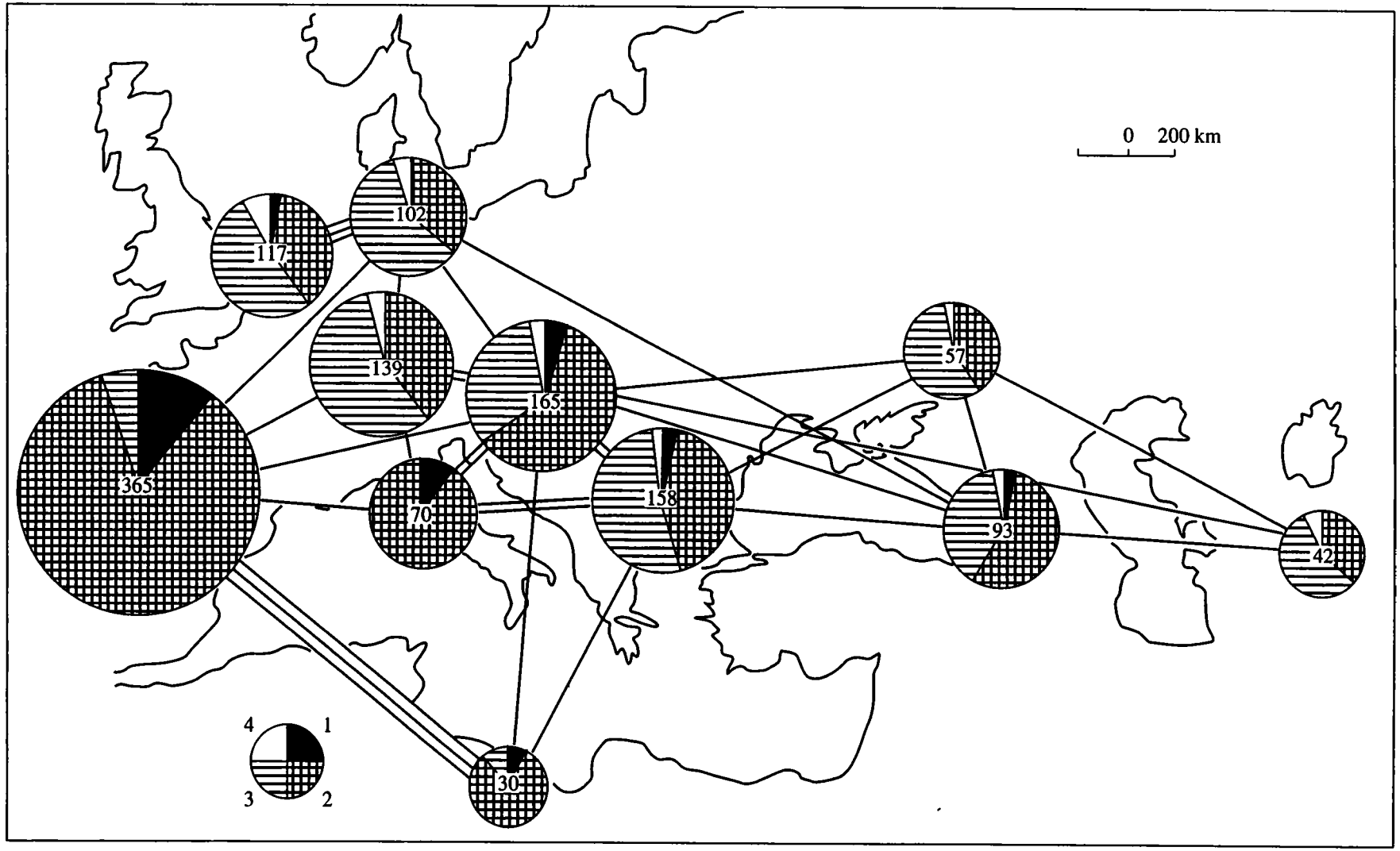

Fig. 1. Circle diagrams of abundance and degree of thermophilic affinity of the early Miocene bivalve mollusks. Circle areas are proportional to the species number, indicated in the center.

1 – tropical species; 2 – tropical–subtropical species; 3 – widespread species; 4 – mostly boreal species. Connecting lines show the degree of compositional similarity between assemblages.

Mollusks from the Aquitanian basin of southern France, the stratotype region for the Aquitanian and Burdigalian (Cossman and Peyrot, 1909 - 1914), are similar in composition to the assemblages described above, but they are more abundant. More than 360 species of 184 genera and subgenera were distinguished in this area. This diversity and the presence of many large forms (giant Pectinidae) and tropical genera (*Trisidos, Codakia, Cardium* s.s., *Bucardium, Discors*, and *Cardiocardita*) associated with variable Lucinidae and Veneridae indicate that the fauna existed in extremely warm-water environments, close to the tropical type. Naturally, a number of species from this diverse fauna are unknown in other regions and in older deposits (65% of species), but many of the species became widespread even in the early Miocene.

The Burdigalian molluscan assemblage of Portugal is less diverse (about 50 species, according to Dollfuss *et al.*, 1903 - 1904). The share of species with a wide occurrence is much greater here, but their composition does not exceed the diversity of the richer Aquitanian fauna.

Transcaucasia. The Sakaraulian molluscan assemblage of Georgia is rather representative (more than 90 species), but, undoubtedly, the known species do not fully reflect the diversity of this fauna. The large sizes of the mollusks, their diversity, and the presence of subtropical and several tropical genera indicate that this assemblage has a warm-water character. Among species with a wide occurrence, there are many forms in common with representatives of the Eggenburgian assemblage of Central Europe, though the considered assemblage is nearly free of species similar to Burdigalian forms, which are also unknown in the Eggenburgian fauna. At the same time, the Sakaraulian fauna includes many allochtonous species that are now considered to be conventional endemics. This fauna is nearly as successive with respect to Oligocene mollusks as the Eggenburgian fauna, and about 40% of the species found here are also known in older deposits.

Central Europe. The upper Egerian and Eggenburgian molluscan assemblages of Romania (Moisescu, 1978), Hungary (Baldi, 1973, 1986), Slovakia (Seneš, 1958; Vanova, 1959), Upper Bavaria (Hölzl, 1958, 1965), and Austria (Schaffer, 1910) are extremely diverse and quite similar to each other (Tables 1 and 2). Nearly half of the species found in these regions are common to South European bivalve molluscs; the majority of them are of warm-water Tethyan genera. At the same time, they are rather unique; more than one-third of the species (36%) are unknown outside of Central Europe. Only those species inherited from the Oligocene and several species of Miocene origin with extremely large distribution areas (*Anadara diluvii, Glycymeris bimaculata, Limatula subauriculata, Parvicardium papillosum, Macoma elliptica,* and *Thracia eggenburgensis*) were in common with mollusks of the Norway-Greenland basin. Forms of Oligocene origin are dominant among those species in common with mollusks of Transcaucasia and Ukraine, but several newly appearing Miocene species are also present, including some unknown in the South European assemblages: *Glycym-*

Table 1. Comparison of the species composition of the Lower Miocene bivalves of western Eurasia

Preston's coefficients

	1	2	3	4	5	6	7	8	9	10	11	12
1 North Africa	**30**	0.82	0.43	0.80	0.70	0.79	0.80	0.90	0.91	0.92	0.94	0.93
2 Italy (+ Spain)	10	**70**	0.80	0.78	0.67	0.75	0.74	0.91	0.84	0.87	0.86	0.90
3 Southern France (+ Portugal)	24	34	**365**	0.79	0.77	0.76	0.73	0.93	0.86	0.95	0.92	0.92
4 Romania	12	28	62	**158**	0.67	0.54	0.61	0.90	0.83	0.85	0.81	0.85
5 Slovakia + Hungary	20	41	68	66	**165**	0.54	0.61	0.89	0.73	0.79	0.77	0.86
6 Austria	13	29	60	58	80	**135**	0.64	0.93	0.90	0.87	0.86	0.91
7 Bavaria	11	30	68	69	72	60	**139**	0.93	0.83	0.87	0.83	0.91
8 Netherlands	7	10	18	18	19	12	12	**117**	0.52	0.92	0.94	0.95
9 Northern Germany + Denmark	6	17	30	27	43	15	26	61	**102**	0.87	0.83	0.90
10 Northern Ukraine	4	11	8	18	23	15	14	8	13	**57**	0.71	0.73
11 Georgia	4	15	19	27	31	20	25	9	21	21	**93**	0.77
12 Transcaspian region	3	8	9	14	12	9	10	6	9	16	18	**42**

Number of common species — Number of species

Note: Semibold numbers placed diagonally indicate species number in the assemblages; high Preston coefficient values are hatched; the coefficients showing the closest connection are doubly hatched (for treshold values see Popov *et al.*, 1993; Popov, 1994).

Table 2. Distribution of Genera (Subgenera) of Bivalves in the Early Miocene Basins of Western Eurasia

Geographical distribution / Genera and subgenera	North Africa	Italy	Southern France	Romania	Slovakia + Hungary	Austria	Bavaria	Netherlands	Northern Germany + Denmark	Ukraine	Georgia	Transcaspian region
I. Distribution is restricted to the Tethys												
Gregariella			1									
Lithophaga			5									
Peplum		1										
Spondylus		2	3									
Liostrea			1									
Exogyra			1									
Pseudolepton			1									
Basterotia			1									
Carditamera			3									
Cardiocardita			2									
Pteromeris			1									
Carditopsis			2									
Loxocardium			1									
Mesodesma			2									
Strigilla			1									
Lutetia			1									
Marcia			1									
Circe			1									
Timoclea			1									
Tivela			1									
Sunetta			1									
Petricolaria			1									
Pleurodesma			4									
Gastrochaena			3									
Degrandia			1									
Martesia			2									
Jouannetia			2									
Xylophaga			1									
II. Distribution is restricted to the basins of the Tethys, Central Europe, and Transcaucasia												
Arca		1	3		1	2					1	
Barbatia (*Obliquarca*)			1								1	
Trisidos	1		1		1							
Septifer			3	1								
Coralliophaga			2			2						
Pinctada			2			1						
Chlamys (*Mimachlamys*)			1		1							

Table 2. (Contd.)

Genera and subgenera / Geographical distribution	North Africa	Italy	Southern France	Romania	Slovakia + Hungary	Austria	Bavaria	Netherlands	Northern Germany + Denmark	Ukraine	Georgia	Transcaspian region
Ch. (Antipecten)			1									
Hinnites			1	2								
Plicatula			2		1							
Lima s.s.	1		2		1							
Crassostrea	1	1	4	3	4	5	1					
Linga			1	1								
Ctena			3									
Codakia			1	1	1							
Felaniella			2				1					
Megacardita		1			1	1						
A. (Tridonta)			2			1						
Crassatella		2			2							
Crassatina						1	1					
Bucardium			1			1						
Anatina			1	1								
Eastonia			3			1	1					
Tellina			1		1							
Phylloda			1				1					
Peronidia			2	3			3					
Angulus (Serratina)			1	1	1		1					
Arcopagia			3		2	1					1	
Gastrana			2	1	1	1	1					
Florimetis		1	1	1		1	1					
Pharus			1			1	1					
Congeria			3		1		1					
Trapezium			1	1								
Miocardiopsis				1								
Periglypta			2		2							
Circomphalus			2	1	2	2	1					
Nitidavenus				1	1							
Venerupis			2		1	1						
Irus			1		1	1						
Tivelina			2		1		1					
Petricola			4		1		1					
Tugonia			1			1						
Corbula (Caryocorbula)			1	1			1					
Spheniopsis		1			1							
Pholas			4		1	2	1					

Table 2. (Contd.)

Genera and subgenera \ Geographical distribution	North Africa	Italy	Southern France	Romania	Slovakia + Hungary	Austria	Bavaria	Netherlands	Northern Germany + Denmark	Ukraine	Georgia	Transcaspian region
Teredo		1	1	1	1	1	1					
Brechites						1						
III. Widespread taxa												
Nucula s.s.		2	4	3	3		3	1	1	1	1	1
N. (*Lamellinucula*)					1		1	1			2	1
Leionucula			1	1	2	1	1	1	1	1		1
"Nuculana"											1	
N. (*Saccella*)				3	2	2	3	1		1	3	
Lembulus			3	1							?	
Yoldia s.s.			2					1				
Y. (*Cnesterium*)				2								
Barbatia s.s.		1	4		2	2	1					
Acar			2					1				
Anadara	4	3	8	5	7	2	3	1	3			
Arcopsis	2		3			1						
Limopsis s.s.								1				
L. (*Pectunculina*)			1	2	1		1	2			1	
Glycymeris		1	3	3	3	2	4	1	1	2	3	2
Mytilus			2	1		3	1				1	1
Arcomytilus												1
Modiolus			2								2	
Modiolula								1				
Musculus	1		2	2				1		1		2
Arcoperna							2	1				
Amigdalum								1				
Atrina	1	1	2	1	1	1	1	1		1	1	1
Isognomon		1	1		2	2				2	1	1
Pteria										1		
Pecten s.s.	2	3	6	6	3	2	1	1				
Pecten (*Flabellipecten*)	1	4	2	1	2					2	1	
Chlamys (*Chlamys*)		5	2	3	4	1						
Ch. (*Aequipecten*)	1	3	2	5	3	3	2					
Ch. (*Macrochlamis*)			1	3	2	3	1			1		
Ch. (*Manupecten*)										1		
Ch. (*Agropecten*)				2				1				
Amussium		1			1							
Propeamussium (*Parvamussium*)				1								
P. (*Pseudamussium*)								1				

Table 2. (Contd.)

Genera and subgenera \ Geographical distribution	North Africa	Italy	Southern France	Romania	Slovakia + Hungary	Austria	Bavaria	Netherlands	Northern Germany + Denmark	Ukraine	Georgia	Transcaspian region
Amussiopecten	1		1					1				
Korobkovia								1				
Anomia	1	1	4	1	2	2	1				1	
Pododesmus								1				
Limaria			1					1				
Limatula			1		1	1		2				
Limea								1				
Ostrea	1		5	4	4	5	3					
Cubitostrea	1	1	2	1	1	1				1		
Pycnodonte	1	1	2	2	1	1					1	1
Neopycnodonte								1				
Lucinoma		3	2	1	2	1	4	1	1	1	1	
Gonimyrtea		1	3	1	1		1	1	1			
Codalucina			1			1					1	
Saxolucina		1	4	3	3	3	3		1	1		1
Megaxinus	1	1	4		1	1	1			1	1	
Anodontia			2	1	1			1	1			
Loripes			2	2	2		1	1				
Divalinga		1	1	2	2	2	1		2	1		
Myrtea			1							1		
Thyasira		1			2		1	1	2			
Diplodonta			3	1			1				1	
Chama		1	6	1	2	2	1	1				
Erycina			5	1	1		2	3	1			
Scacchia			2					1	1			
Kellia			7	1			1	1				
Lepton			1					1	1			
Spaniorinus			2					2	1			
Anisodonta			4		1	1		2	1			
Lisaeina			4	3			2	1	1			
Cardita		1	2			1				1	1	
Glans			2		1			1				
Scalaricardita		1	1		1	1			3		1	
Astarte (*Astarte*)		2		3	4			3	4	2	2	
A. (*Digitaria*)			1	1				1	3			
Goodallia			1					3	1		1	
Cardium		1	4	2	3	2	2		1		1	
Europicardium		1	4	1	1	1	1			1	1	

Table 2. (Contd.)

Genera and subgenera \ Geographical distribution	North Africa	Italy	Southern France	Romania	Slovakia + Hungary	Austria	Bavaria	Netherlands	Northern Germany + Denmark	Ukraine	Georgia	Transcaspian region
Laevicardium			1	1	2	2		1	1	1	3	
Plagiocardium			1							1	2	1
Acanthocardia			4	8	5	3	5		1		4	
Parvicardium			4	1	4	1	3	2	3		3	
Cerastoderma			1	2	1	2	1		1	1	1	2
Discors		1	2	1							1	1
Nemocardium (*Habecardium*)		2		1	2	1	2	1	3	1	2	
Mactra			4	2	2	2	3	1	2		1	
Spisula	1		3		1	1	1	1	1			
Lutraria		3	5	4	4	2	4	1	1		1	
Ervilia			1					1	1		1	
Solen			2	1		1	1			1		
Cultellus					1		1	1	1			
Ensis			1	1	1		2	1	1	1	1	
Angulus (*Omala*)				2	2	2	2	1	1	1	3	1
A. (*Moerella*)				1	2	1		3	2			1
Peronaea			2	2	3	2	1				2	2
Macoma		1		1	1	1	1	1				
Donax			3	1			2		1		2	
Gari			6	3	3	1	4				1	
Abra			1		1			5	4		1	
Solecurtus			1	1	1		1	1	1	1		
Azorinus	1		1	1	1	1		1	1			
Arctica		1	1	1	2	1	1	1	2	1	2	
Glossus			1	3	2	3	1	1	4	2	2	1
Polymesoda			3		3		4				1	
Venus	1	1	4	5	3	3	4	1	1	2	3	2
Callista		3	1	5	5	3	3		1	4	5	2
Pitar			3	1			1		1			
Paphia			5	2	3	3	1				1	
Clausinella	1		7	4	2		2	1				
Grateloupia		1	2				1					
Gouldia			1		1			1	1			
Dosinia	1	1	4	3	2	1	3		1		1	
Pelecyora		1	4	3	3	3	2	1	1	1	2	2
Sphenia			5		1		1	1	1	1	1	1
Corbula (*Corbula*)			4	2	2		1		1			
C. (*Varicorbula*)	1	1	1	1	1	1	1	1	1	1	1	1

Table 2. (Contd.)

Genera and subgenera / Geographical distribution	North Africa	Italy	Southern France	Romania	Slovakia + Hungary	Austria	Bavaria	Netherlands	Northern Germany + Denmark	Ukraine	Georgia	Transcaspian region
Lentidium			3				1		1	3	2	2
Hiatella			1			1		1	1			
Panopea	1	1	2	1	2	1	1	1	1	3	1	2
Cyrtodaria			1			1	1	1	1	1	1	1
Aspidopholas			1					1				
Pholadomya		1	2	4	4	1	2	1	2		1	1
Pandora			1					1	1			
Conchlodesma			1					1				
Thracia		3	4	4	3	2	3	3	2	1	2	1
Cuspidaria		1	3		1	1	1	1	1		1	1
Clavagella			2					1				
IV. Genera occurring only in basins of Northern Europe and the eastern Paratethys												
Yoldiella								1				
Axinulus								1				
Aligena								1				
Mioerycina								1				
Properycina								1				
Montacuta								1				
Mysella								1	1			
Cardites										1		
Erycinella								1				
Astarte (*Laevastarte*)									1			
Gonilia								1				
Monterosatus								1				
Oudardia									1			
Pygocardia								1				
Alveinus								1	1			
Meiocardia								1	1			
Janschinella												1
Corbula (*Lenticorbula*)								2	2			
Lyonsia								1			1	
Poromya								1				
Cardiomya								1	1			
Verticordia								1				
Haliris								1				
Number of species	30		365		229		158		102		93	
		70		158		135		117		57		42
Number of genera (subgenera)	24		184				90					
		46		90		80		94	64	40	59	30

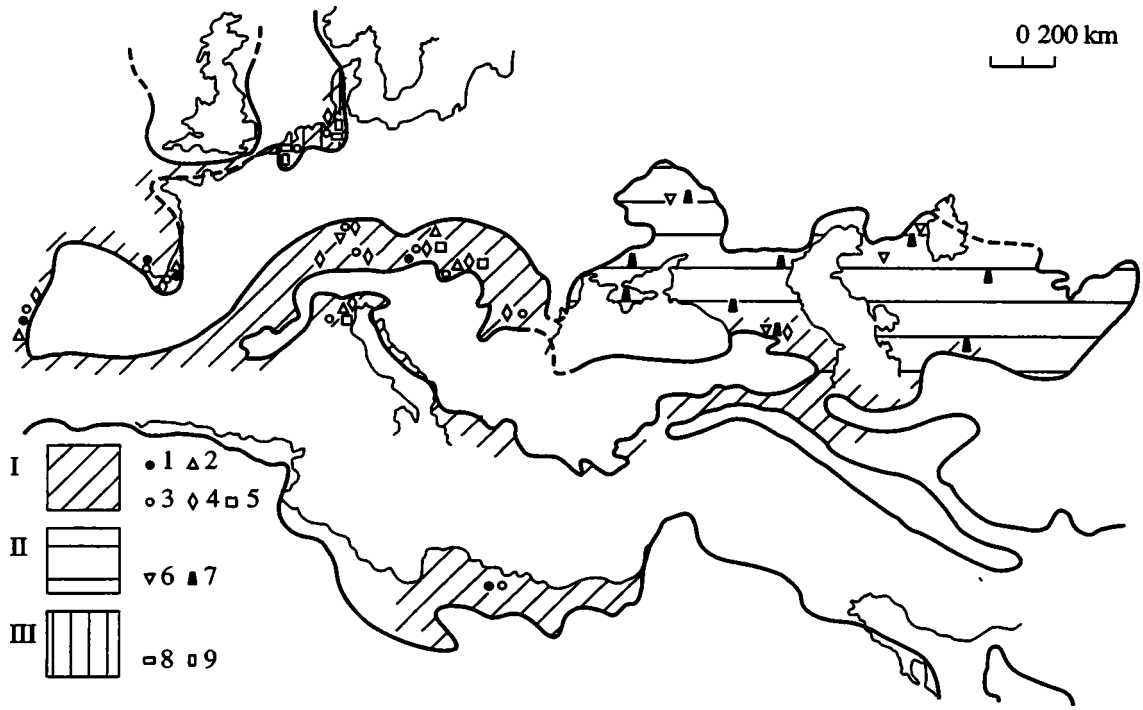

Fig. 2. Distribution areas of some characteristic genera and species of the early Miocene bivalves.
I – Tethyan genera: 1 – *Lima*, 2 – *Spondylus*, 3 – *Pecten* s.s., 4 – *Cardium* s.s., 5 – *Crassatella*; II – endemics of eastern Paratethys: 6 – *Callista uretzkii*, 7 – *Plagiocardium abundans*; III – endemics of the Northern Sea: 8 – *Astarte angulata*, 9 – *Laevicardium dingdense*.

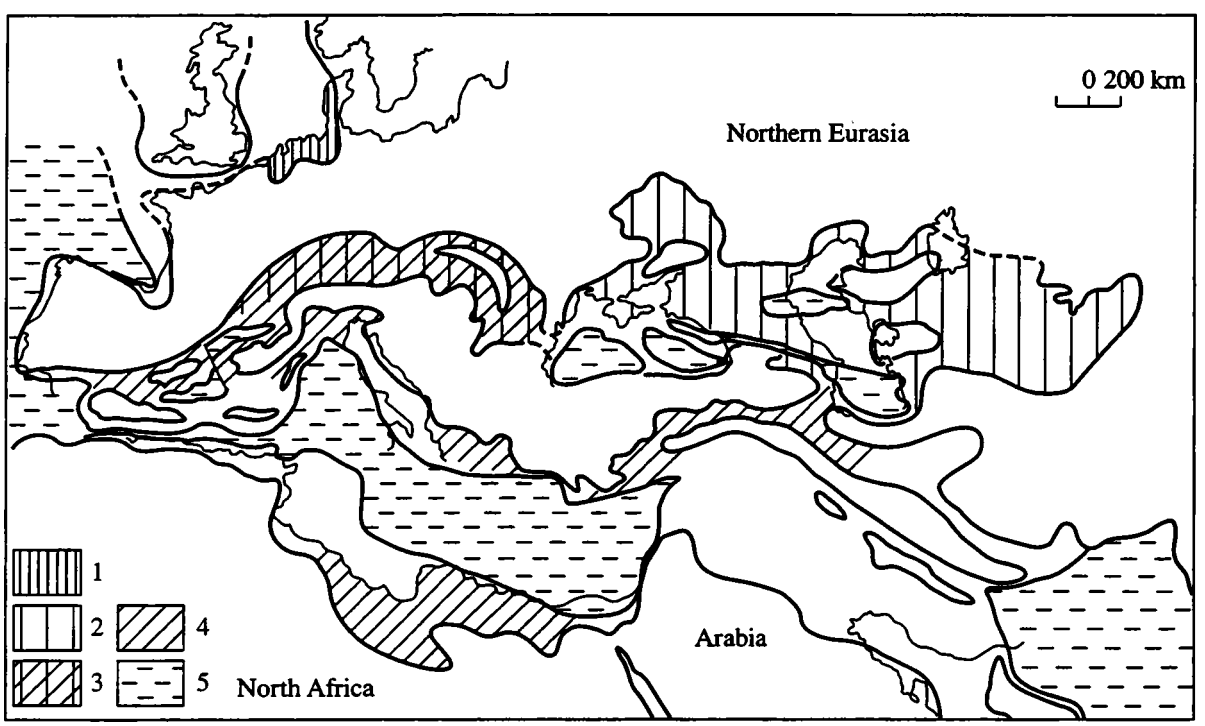

Fig. 3. Scheme of zoogeographic zonation of the West Eurasian shelf in the early Miocene according to bivalves.
1 – German province; 2 – Eastern Paratethys; 3 – Central Paratethys; 4 – Mediterranean; 5 – deep basin parts outside shelf areas.

eris fichteli, Laevicardium Spondyloides, Acanthocardia grande, Parvicardium heeri, Fragum semirugosum, Donax intermedius, Glossus maior, Callista lilacinoides, and *Corbula modelli*. The inheritance degree of this fauna with respect to the Oligocene assemblages can be evaluated rather differently depending on what is being considered, the upper Egerian or the Eggenburgian molluscan assemblages. Many scientists believe that it is impossible to confidently distinguish the upper Egerian fauna from the lower Egerian one. At the same time, the Eggenburgian fauna mainly consists of species that appeared in the Miocene time, because the share of Oligocene species here is about 30%.

Northwestern Europe. Representative assemblages of lower Miocene bivalves are known in northern Germany (Kautsky, 1925; Anderson, 1959; Hinsch, 1972; Janssen, 1972) and the Netherlands (Janssen, 1984). The Hemmoorian bivalves (nearly corresponding to the Burdigalian fauna) are the most abundant. The Virlandian fauna has a transitional composition and includes species characteristic of both the Oligocene and the Miocene epochs.

As in every other region, abundant warm-water groups that are characteristic of the Miocene appear in the above faunas. *Anadara diluvii, Venus multilamella, Pitar rudis, Acanthocardia, Dosinia*, and others had already appeared during the Virlandian. However, the share of species inherited from the Oligocene is still significantly higher in these assemblages [more than 70%, according to Hinsch's (1972) data on drilling cores in northern Germany]. During the Hemmoorian, the composition of bivalve assemblages was diversified by the appearance of even more thermophilic forms, and the share of subtropical genera became as high as about 30%. *Acar, Atrina, Limidae, Chama, Megaxinus, Anodontia, Glans, Cardium* s.s., *Venus*, and other taxa appeared at this time. The share of Oligocene species decreased to 40%. In addition to Miocene species and genera with wide occurrences, the faunas include many endemics that are unknown outside of Northwestern Europe (group IV in Table 2). The Netherlands assemblage (Janssen, 1984) is the most original. This results from both the initial peculiarity of this fauna and the degree of its preservation, which enabled a thorough study; many small, thin-walled forms were described in this assemblage.

Eastern Europe. A molluscan assemblage that is presumably Aquitanian in age is known from the Sivash Subformation of Ukraine. Due to poor preservation, many of its forms were identified tentatirely at the cf. or generic levels. Nevertheless, many thermophilic genera and species, such as *Atrina, Isognomon, Divalinga, Europicardium, Venus* cf. *multilamella, Callista lilacinoides, Glycymeris pilosa deshayesi, Glossus maior*, and others, are undoubtedly present here. These forms suggest that the assemblage is correlative with the upper Egerian molluscan faunas of Central Europe. The relatively high difference coefficients between the Sivash and upper Egerian assemblages (Table 1) are accounted for by the fact that, among 57 forms, only 28 species are identified precisely. In addition to Miocene immigrants, the Oligocene species represent a significant part of the assemblage. It also includes species that are endemic to the eastern Paratethys (*Plagiocardium abundans, Cerastoderma prigorovskii*, and *Sphenia nana*).

The molluscan assemblage from the Ol'ga Formation of Ciscaucasia is poor. It is free of thermophilic forms and cannot be correlated with the described faunas because of the deep-water origin of the taxa.

Transcaspian region. The molluscan assemblages of Kyzyl-Kum, southeastern Turkmenia, and Tadzhikistan are rather poor and badly preserved; however, according to their generic composition, zoogeographical characteristics, and inferred ages, they may be correlative with the Sivash assemblage. For instance, *Atrina, Isognomon, Megaxinus, Glycymeris pilosa deshayesi, Venus* sp., and *Callista lilacinoides* were also found here.

COMPARISON OF ASSEMBLAGES AND ANALYSIS OF THE CHARACTERISTIC AREALS OF GENERA AND SPECIES

It is easily seen from the results of the in-pair comparison of common species for each pair of assemblages (Preston's coefficients) of the lower Miocene bivalves (Table 1) that a tendency for differences to decrease that appeared during the Chattian time continued to progress later (the greater differences in the Netherlands assemblage were caused by other factors, see above). The closest relations were distinguished between faunas of the central European basins and between them and faunas of the Mediterranean Tethys, including faunas of the North African coast and Aquitanian basin. Against this background, differences of faunas from the eastern Paratethys are undoubtedly exaggregated by incomplete data and uncertain determinations. In addition, the low degree of similarity between these faunas is caused by their age differences: the Sakaraulian fauna undoubtedly corresponds to the Eggenburgian or, probably, to the early Ottnangian, while the Sivash and Transcaspian molluscan assemblages are older and probably coeval with the late Egerian fauna.

Among species that were the most widespread during the early Miocene, there are both forms that had existed since the Oligocene (*Lucinoma borealis, Nemocardium cingulatum, Corbula gibba*, and others) and new Miocene species (*Anadara deluvii, Atrina pectinata, Europicardium multicostatum*, and others). A significant part of the latter group is represented by species that exist today (*Glycymeris bimacilata, Divalinga ornata, Chama gryphoides, Parvicardium papillosum, Hiatella arctica*, and others). Some species that were found only in the most thermophilic southern assemblages of the Chattian time (*Anodontia fragilis, Pecten*

burdigalensis, Macoma elliptica, Venus multilamella, and *Pholadomya alpina*) became widespread.

Species restricted in distribution to the Mediterranean Tethys and the Central European basins (more than 100 species; group II in Table 2, Fig. 2) were extremely abundant. Species that are probably of Tethyan origin and are known since the Miocene are dominant among them.

Species endemic to the Central European basins were even more abundant. There were also many species that had existed since the time of the Egerian molluscan assemblage and those that appeared in the Eggenburgian time. Later, some of them migrated to the Mediterranean area. Their greater diversity (about 140 species) probably results from the fact that these assemblages are better studied.

As mentioned above, the inherited Oligocene species predominated among bivalve assemblages common to Central Europe, the Eastern Paratethys, and northwestern Europe, thus indicating the difficulty of such migrations during the Miocene.

ZOOGEOGRAPHICAL PROVINCES

The North European subregion, which is distinguishable (according to publications) since at least the Cretaceous, probably disappeared at the beginning of the Neogene. Since the beginning of the Burdigalian (Eggenburgian, Sakaraulian, and Hemmoorian), molluscan assemblages of the entire studied region became similar enough to be considered as fauna of a single Mediterranean tropical–subtropical subregion, which was probably a part of the Tethyan region. However, a more detailed study will possibly show that the North Atlantic fauna was independent, and that the Neogene fauna of the Norway-Greenland basin should rather be referred to the Atlantic subregion. In any case, it was not a part of the North European subregion inherited from the Paleogene, because the composition of the fauna and zoogeographical connections changed significantly (Fig. 3).

Undoubtedly, the late Egerian and Eggenburgian basins of Central Europe had rather similar faunas, probably characterizing a single Central European subtropical province with tropical elements. In the Miocene, it included the Southern Bavaria basin, which was a constituent of the German province during the Chattian.

Data on provincial fauna of the eastern Paratethys for the beginning of the Miocene are scarce. At the very beginning of the Miocene, this province probably remained independent, and endemic species inherited from the Oligocene fauna determined its peculiarity and difference from the Central European province. Nothing is known about the shallow marine mollusks of the later (Sakaraulian) period from the northern part of the eastern Paratethys. In the southern Transcaucasian part of the basin, the Sakaraulian province is distinguishable. It was also probably a part of the Mediterranean subregion but had other connections with the ocean in addition to those on the western side, which was probably open to the Indian–Persian region. It is possible that the Kopet-Dag part of the basin was also a part of the Sakaraulian province, but so far the data suggesting this are extremely scarce.

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BRIEF COMMUNICATIONS

Neogene-Quaternary Nannoplankton of DSDP Site 362, the South Atlantic

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Key words: *Stratigraphy, nannoplankton, biostratigraphic zone, Neogene, Miocene, Pliocene, Pleistocene, and upwelling.*

Hole 362, drilled during Leg 40 of the Deep Sea Drilling Project by D/V *Glomar Challenger,* is located on the Abutment Plateau of the Frio Ridge segment of the Walvis Ridge, where it adjoins the continental margin of South Africa, at 19°45.45'S and 10°31.95'E. It penetrated a thick Pliocene-Quaternary sequence represented by diatomaceous nannofossil ooze. According to Bolli and coauthors (Bolli and Ryan *et al.*, 1978), only the upper Core 362-1 was referred to the Pleistocene, based on planktonic foraminifer and nannofossil evidence. The interval of Cores 362-2 to 5 was referred to the *Emiliania ovata* nannoplankton zone, whereas the sediments of Cores 362-2 to 4 yielded upper Pleistocene radiolarians. Cores 362-5 through 10 did not contain index species of nannofossils and warm-water planktonic foraminifers, but the composition of their assemblages presumably indicated a Pleistocene or Pliocene age (the figure). Downward from the base of Core 362-7, the sediments were dated according to planktonic foraminifers. The base of the Pliocene was defined between cores 362-14 and 15 by means of foraminifers and nannoplankton.

The diatom records referred Core 362-1 (36 to 45.5 m below the sea floor) to the Pliocene *Pseudoeunotia doliolus* Zone. The species composition in Cores 362-2 to 4 indicated the Pliocene-Pleistocene boundary. Cores 5 to 7 were referred to the Pliocene *Rhizosolenia praebergonii* Zone; Cores 362-8 to 10, to the *Nitzschia jouseae* Zone; and Cores 362-10 and 11, to the *Thalassiosira convesea* Zone. The sediments of Cores 362-11 through 22 did not yield stratigraphic markers. The Miocene-Pliocene boundary was defined within the interval of Cores 362-23 to 27 (330.5 - 416 m) in the *Coscinodiscus yabei* Zone.

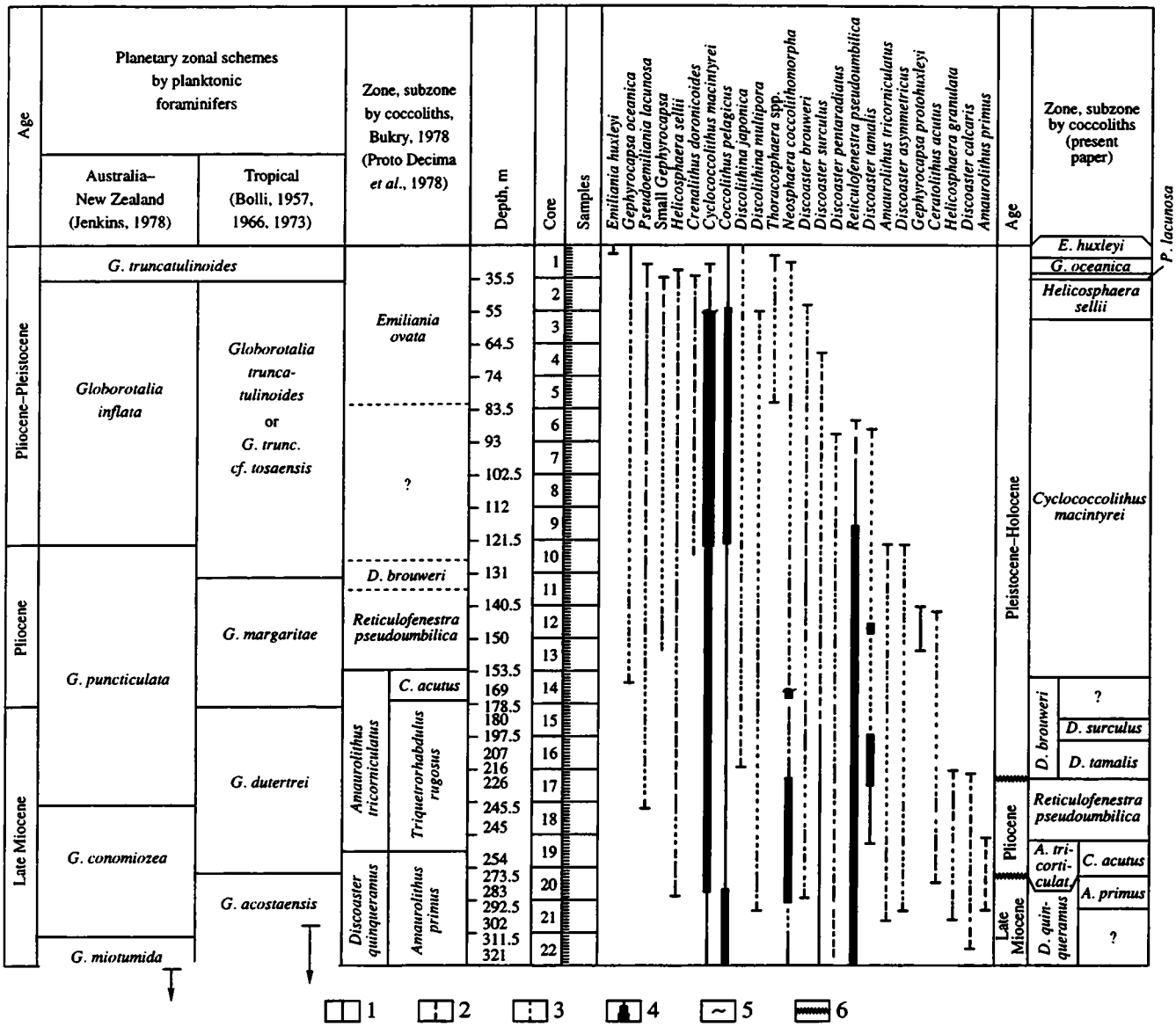
Calcareous nannoplankton was examined in 196 samples taken from each section of the 22 cores using the "Amplival" 225-power light microscope (121 sample) and the JSM-U3 14 000-power scanning electron microscope (75 samples). The purpose of the investigation was to distinguish nannofossil assemblages and their species composition, preservation, abundances, and peculiarities as well as to perform a detailed subdivision of the section using the standard nannoplankton zonations (Gartner, 1977; Bukry, 1978).

Preliminary study of nannoplankton was carried out by F. Proto Decima during Leg 40 (Proto Decima *et al.*, 1978), but it was almost not reinforced by electron microscopy.

The calcareous nannoplankton assemblages appear to be heterogeneous due to the strong dissolution and redeposition of nannofossils, which occurred persistently during sediment accumulation and resulted in the reworking of ancient species into younger deposits and the removal of certain species from the assemblage. Local unstable conditions could have resulted from the influence of the adjacent zone of upwelling, which was periodically strengthened. The latter events were accompanied by a decrease in species diversity and an abundance mainly among small coccoliths due to mechanical transportation, when small forms including zonal index species disappeared, strongly hampering the definition of the exact zonal correspondence of assemblages.

Despite the presence of allochthonous coccoliths and, as a result, the substantial "offensive" of lower nannofossil zones in the upper ones, I succeeded in defining more precisely the Pliocene-Pleistocene boundary (in Core 362-14) and subdividing the Quaternary section into several zones according to Gartner's scheme. I was also able to distinguish Pliocene zones in the sediments of Cores 362-14 through 19 (the figure).

The upper part of the Quaternary section represents a continuous succession of upper Pleistocene deposits. The following nannofossil zones were identified downward from the top. The *Emiliania huxleyi* Zone (0 - 0.27 Ma) was distinguished in the interval from Sample 362-1-1 (9-10 cm) to Sample 362-1-2 (93-95 cm). The base of the zone is defined by the index species appearance. The next *Gephyrocapsa oceanica* Zone (0.27 - 0.44 Ma) represents an interval between the first occurrence of *Emiliania huxleyi* (Lohm.) Hay, Mohl. and the last occurrence of *Pseudoemiliania lacunosa* (Kpt.) Gart. The disappearance of that species, in turn, indicates the upper boundary of the *Pseudoemiliania*



Vertical distribution of nannoplankton species in the Neogene-Quaternary of Site 362.

1, 2 – occurrence: 1 – continuous; 2 – discrete; 3 – proposed occurrence; 4 – change in abundance; 5 – change in coccolith dimensions from smaller to larger downward the section; 6 – hiatuses.

lacunosa Zone, whereas its base is correlated with the last occurrence of *Helicosphaera sellii* Bukry, Bram. and *Crenalithus doronicoides* (Black, Barn.) Roth. The zone is distinguished in Sample 362-1-6 (9 - 10 cm). The next interval of deposits between Samples 362-1 (CC) and 362-2-1 (120 - 122 cm) corresponds to the *Helicosphaera sellii* Zone, which is correlated with the top of the *Crenalithus doronicoides* Zone of Bukry's scale. It should be noted that the last occurrence levels of the index species were strongly overstated in the studied section due to the constant redeposition of material into the overlying sediments. It seems probable that the smaller the dimensions are and the higher the abundance of coccolith, the longer their burial is in the sediments. For instance, this is the reason for the simultaneous disappearance of *Helicosphaera sellii* and *Crenalithus doronicoides* at Site 362, though the last occurrence of the latter was recorded earlier in other sections. This does not permit the correlation of last occurrence levels of index forms with the oxygen isotope datums established for them in other localities.

The zone of small *Gephyrocapsa* of Gartner's scheme was not distinguished in the section. The number of small coccoliths, including *Gephyrocapsa*, increases in the interval between Samples 362-2-2 (120 - 122 cm) and 362-3-4 (90 - 92 cm). The upper boundary of their epibole is therewith placed lower

than the last occurrence of *Pseudoemiliania lacunosa*, reflecting the natural evolutionary development of the species, which is also characteristic of other localities. The epibole of small *Gephyrocapsa* is poorly pronounced at Site 362 owing to dissolution, which resulted in poor preservation of small coccoliths and distortion of stratigraphic relationships with *Crenalithus doronicoides* and *Helicosphaera sellii*.

Downward from Sample 362-3-2 (90 - 92 cm), the *Cyclococcolithus* (= *Calcidiscus*) *macintyrei* Zone occurs. Its upper boundary corresponds to the top of the index species epibole and to the beginning of the decrease in its coccolith dimensions upward the section. This zone is clearly recognized down to the level 362-6-3 (90 - 92 cm). In the interval from 362-6-3 (90 - 92 cm) to 362-14-2 (90 - 92 cm), the sediments contain a mixed Pliocene-Pleistocene assemblage. In most of the interval, gephyrocapses are almost entirely absent; only disks of dissolved forms were recorded. *Cyclococcolithus macintyrei* Bram., Bukry; *C. leptoporus* (Murr., Blackm.) Kpt.; and *Coccolithus pelagicus* (Wall.) Schill., characteristic of both the lower Pleistocene and the upper Pliocene, are the main components of the assemblage. It would be extremely difficult to distinguish the Pliocene-Pleistocene boundary using such material. However, in the lower part of this member, from Sample 362-10-1 (90 - 92 cm) to Sample 362-14-2 (90 - 92 cm), the abundance of small coccoliths increases again; *Gephyrocapsa oceanica* Kpt. [up to 362-12-6 (90 - 92 cm)]; *G. sinuosa* Beaudry, Hay; and *Pseudoemiliania lacunosa* were identified here. At the base of this interval, the deposits yield disks of dissolved gephyrocapses, and only from the Sample 362-14-5 (90 - 92 cm) does all evidence of Quaternary forms completely disappear, indicating the Pliocene age of the sediments. It is noteworthy that single *Discoaster tamalis* Kpt. and *D. pentaradiatus* Tan occur as high as in Sample 362-5-4 (90 - 92 cm), though this should not be taken into account, because redeposited species are distributed throughout the whole sequence. The lower part of the Quaternary section also yields small *Reticulofenestra*, recorded up to Sample 362-6-4 (90 - 92 cm). These coccoliths are occasionally encountered within the lower Quaternary section; however, their number sharply rises through Cores 13 to 14 together with increased dimensions.

The Pliocene sediments below the level 362-14-5 (90 - 92 cm) contain a nannofossil assemblage with dominant *Reticulofenestra* and *Cyclococcolithus macintyrei*. Small *Reticulofenestra pseudoumbilica* (Gart.) Gart. constitute about half of the assemblage; larger *R. haqii* Backm. and *Cyclococcolithus macintyrei* are common, and *Coccolithus pelagicus* are scarce. Other species are rare or single, comprising less than 1% of the total assemblage. The upper Pliocene *Discoaster brouweri* Zone, according to the scheme of Bukry (1978), is subdivided into four subzones: *Calcidiscus macintyrei, Discoaster pentaradiatus, Discoaster surculus*, and *Discoaster tamalis*. Sediments in the interval from Sample 362-14-5 (90 - 92 cm) to Sample 362-15-4 (90 - 92 cm) I conventionally referred to the upper Pliocene, to the top of the *Discoaster brouweri* Zone. The index species and *D. pentaradiatus* are scarce here, whereas at this stratigraphic level in similar climatic zones, they constitute, as a rule, a considerable part of assemblages. This indicates unfavorable conditions of burial and does not permit the exact correlation of sediments with subzones of Bukry's scale. The lower Pleistocene and a substantial higher part of the Pliocene deposits appear to have been partly eroded here.

Discoasters, in particular, *Discoaster surculus* Mart., Bram., a subzonal index species of the *Discoaster brouweri* Zone, become gradually more numerous downward from Sample 362-15-5 (90 - 92 cm) (the figure). The subzone is also represented only by its lower part.

Discoaster tamalis Subzone, the lower subdivision of the *Discoaster brouweri* Zone according to Bukry's scheme, with an age of 2.5 - 3 Ma, was identified downward the section in the interval from Sample 362-15-5 (90 - 92 cm) to Sample 362-17-1 (9 - 10 cm). Its upper boundary corresponds to the top of the epibole, whereas the base coincides with a decrease in the index form abundance. Both subzones were distinguished against a background of mass accumulations of *Reticulofenestra pseudoumbilica*. Small coccoliths of that species can be easily redeposited; therefore, biostratigraphic subdivisions based on larger taxa (discoasters) are more reliable. The *Discoaster tamalis* epibole is, in my opinion, the most trustworthy biostratigraphic marker in the studied section. In the *Discoaster tamalis* Subzone, *Discolithina multipora* (Kpt., Defl.) Mart. and larger *Neosphaera coccolithomorpha* Lecal-Schlaud. became more numerous as well as *Rhabdosphaera clavigera* Murr., Blackm.

The early Pliocene *Reticulofenestra pseudoumbilica* Zone, dated as 3 to 4 Ma according to Okada and Bukry (1980), was distinguished between Samples 362-17-2 (90 - 92 cm) and 362-20-2 (90 - 92 cm). It yields a diverse coccolith assemblage with an increased number of discoaster species. *Discoaster deflandrei* Bram., Ried. was identified in its lower beds, and *D. asymmetricus* Gart. also occurs in some samples, though both species are rather scarce. The index species dominating in the assemblage is well-preserved and is often represented by unbroken coccospheres. This indicates their rapid accumulation in the sediment and the absence of dissolution.

Beginning with Sample 362-19-4 (90 - 92 cm), mass fragments of *Ceratolithus acutus* Gart., Bukry occur. The corresponding subzone within the *Amaurolithus tricorniculatus* Zone was distinguished in the section with its lower boundary at the level of Sample 362-19-6 (90 - 92 cm). The upper boundary is dated as 4 Ma.

Downward the section in Sample 362-20-2 (90 - 92 cm), *Discoaster quinqueramus* Gart. was identified. Though it does not continuously occur in the sediments above the lowest studied sample in the section [362-22-4 (90 - 92 cm)], I conventionally distinguished

a corresponding zone with an upper boundary dated at 5.6 Ma (the figure).

Therefore, the Pliocene deposits in the interval from Sample 362-14-5 (90 - 92 cm) to Sample 362-22-4 (90 - 92 cm) include the following (downward):

– the late Pliocene *Discoaster brouweri* Zone with the incomplete *Discoaster surculus* and *Discoaster tamalis* subzones in its lower part;

– the early Pliocene *Reticulofenestra pseudoumbilica* Zone; and

– the *Amaurolithus tricorniculatus* Zone with the *Ceratolithus acutus* Subzone of the early Pliocene.

The upper Miocene sediments of the *Discoaster quinqueramus* Zone occur below the studied part of the section.

Three distinct, rather short hiatuses were recorded: one at the Pliocene-Pleistocene boundary, another within the *Discoaster brouweri* Zone, and a third at the Miocene-Pliocene boundary. The constant reworking of older nannoplankton species into younger deposits resulted both in the overstating of biostratigraphic boundaries, particularly pronounced in the Pleistocene, and in the distortion of the real volumes of the subdivisions. During periods of bottom current decay and strong input of allochthonous material, the sediment thickness increased, as in the *Cyclococcolithus macintyrei* Zone. In contrast, during periods of current strengthening, the sediments were partly eroded, which was characteristic of the entire Pliocene section. Many zonal index species are absent due to ecological conditions, which prevented their mass occurrence and led to the dissolution of small forms, including *Gephyrocapsa*, or to the fragmentation of *Ceratolithus, Amaurolithus,* and *Discoaster* specimens.

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BRIEF COMMUNICATIONS

Paleocene Sea Transgressions in the Framing of the Siberian Platform

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Abstract – Microphytoplankton finds in Paleocene deposits in the southwestern Siberian platform (the Sukhoe bauxite deposit on the eastern slope of Enisei Ridge) and in the upper Paleocene - lower Eocene deposits of the northeastern framing of the platform (Kunga graben in the northern Verkhoyansk region) are discussed. Both localities are far from the reconstructed coastal lines of the late Paleocene and early Eocene seas. It is supposed that the sea ingressed along the sublatitudinal foredeep from western Siberia and along the rift grabens to the northern Verkhoyansk region.

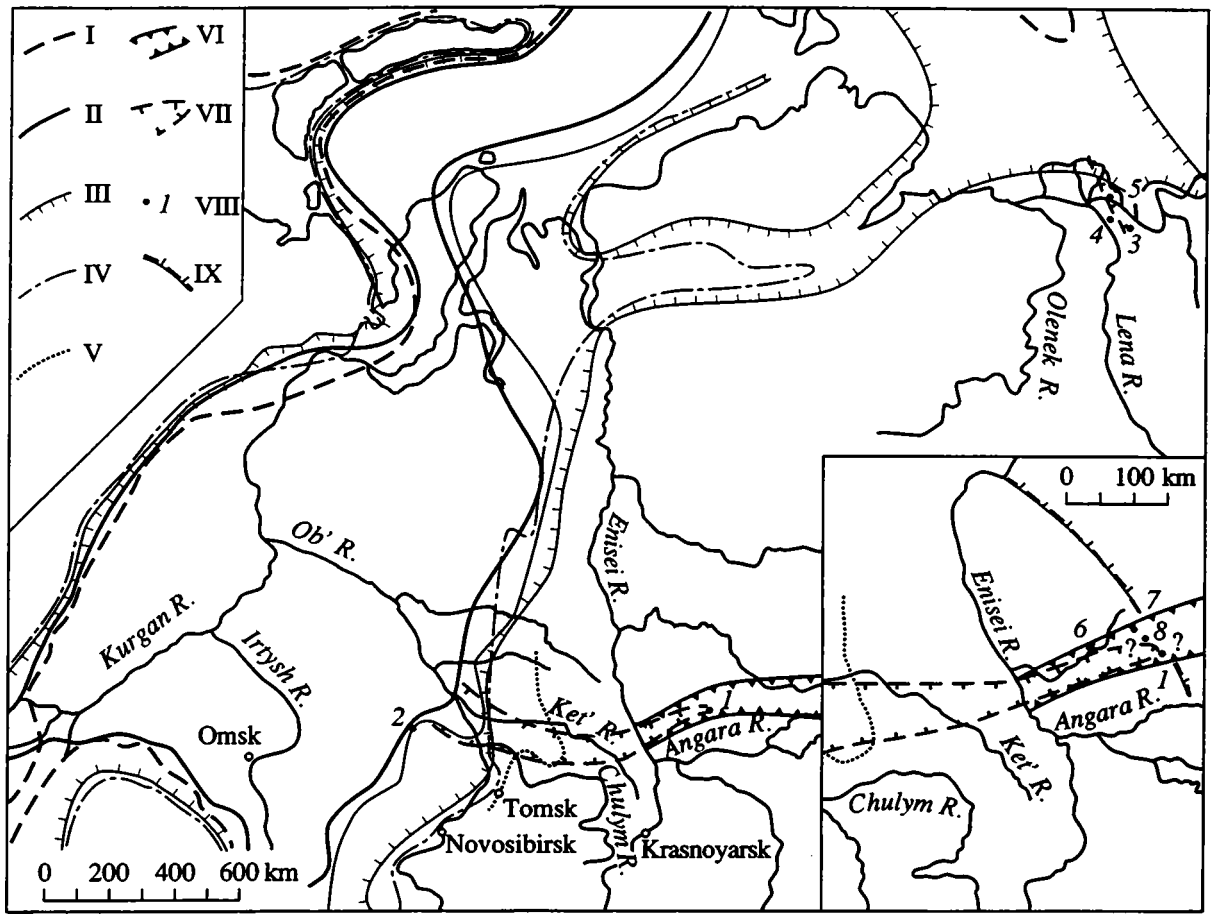
Key words: *Sea transgressions, Paleocene, Siberian platform, microphytoplankton, geochronology, and palynocomplexes.*

It has been suggested that the maximum Paleogene sea transgression in the framing of the Siberian platform occurred in the middle or even the late Eocene (Grossgeim, 1975; Golbert *et al.*, 1977; Yasamanov, 1978; Shatsky, 1978; Laukhin, 1987; and others). For this reason, little attention has been paid to finds of Paleocene microphytoplankton in the northwestern Siberian platform (Laukhin and Kul'kova, 1973a) and in the northeastern part of its framing, namely in the northern Verkhoyansk region (Budantsev *et al.*, 1989). Microphytoplankton was found far from the reconstructed Eocene and Paleocene coastal lines. Even the most resolute reconstructions for the northern Verkhoyansk region (*Paleogeographic Atlas ...*, 1991) suggest that the position of the sea coast in the early Eocene was 30 - 40 km north of the Bykovskii canal and 150 km north of the Kunga graben, the localities from which the finds of microphytoplankton were reported (Budantsev *et al.*, 1989). The Paleocene sea coast is shown shifted 700 km to the north in this atlas (the figure). Therefore, these finds in the Siberian platform and its northeastern framing have to be discussed in more detail. Unfortunately, the microphytoplankton from both regions have not been studied carefully, and the published taxonomic lists are poor and, thus, of low geochronologic significance. The age of the host rocks in both regions was determined confidently, mainly according to palynologic data.

In the southwestern Siberian platform, microphytoplankton was found in amounts of 2.7 - 26.3% (usually 6.5 - 15%) of the total composition of the palynospectra determined in well 850, which is the Paleogene section of the Sukhoe bauxite deposit; it is located on the eastern slope of the Enisei Ridge along the Sukhoe Creek, a tributary of the Kamenka River (the figure, point *1*). These amounts of microphytoplankton are not insignificant, because in well 37, drilled through the western Siberian (the figure, point *2*) deposits of the open sea, the content of middle Eocene microphytoplankton at a depth of 163 - 150 m is 7.8 - 12% (Kul'kova and Shatskii, 1984).[1] According to I.A. Kul'kova, microphytoplankton from well 850 is represented by *Ovoidites* (including *O. microligniolus*), which prevails in two-thirds of the samples, or by *Planctonites* (including *P. stellarius*), which prevails in one-third of the samples; *Ptermospermopsis* forms were noted rarely (Laukhin and Kul'kova, 1973a). It is disputable that *Ovoidites* are typical only of sea conditions; but solely the presence of *Planctonites*, which compose 1.5 - 11.6% of the palynospectra, clearly suggests the sea (or littoral marine) genesis of the host deposits in well 850. In association with microphytoplankton, these deposits contain palynospectra of the late Paleocene, palynocomplex B (Laukhin and Kul'kova, 1973b; Kul'kova and Laukhin, 1975). With due regard for these facts, we may consider possibilities of distant sea ingression on the Siberian platform during the late Paleocene.

A version that reconstructs the widest transgression of the Paleocene - Eocene sea in western Siberia is shown in the figure. The Eocene transgression was more extensive than that of the Paleocene, as follows from the position of coast lines shown in the southwest of western Siberia. The coast lines inferred in the Ket' and lower Chulym river basins approach the Sukhoe deposit (well 850), which bears microphytoplankton. However, even in this reconstruction, the sea coast is placed 600 - 610 km away from the Sukhoe deposit for the Eocene and 740 - 830 km away for the

[1] At other depths, the content of microphytoplankton was either lower or considerably higher.



The location of sections with microphytoplankton in the southwestern Siberian platform and its northeastern framing. Inserted map shows the supposed path of sea ingression from the lower courses of the Ket' to the Sukhoe deposit.

I - V – reconstructed limits of the maximum sea transgressions during the Paleocene and Eocene: up to the mouth of the Kotui river after Shatskii (1978) and eastward according to *Paleogeographic Atlas* ..., 1991; I – for the early Paleocene, II – for the late Paleocene, III – for the early Eocene, IV – for the middle of late Eocene; V – the Eocene maximum of transgression after Dargevich and Lysenko (1984); VI – Bol'shoi Pit depression; VII – trend of the late Paleocene transgressions; VIII – sections, discussed in the paper (*1* – well 850 at the Sukhoe deposit; *2* – reference well 37; *3* – Kunga graben; *4* – Kengdei graben; *5* – Bykovskii canal, *6* - *8* – bauxite deposits of the Bol'shoi Pit depression: *6* – Balandin, *7* – El'chim, *8* – Kardakan); IX – the eastern slope of the Enisei Ridge.

Paleocene. In addition, the sea basin of western Siberia was separated from the Sukhoe deposit in the Paleocene - Eocene (as it is now) by the uplifted western border of the Siberian platform. Currently, this uplift is manifested in relief as the Enisei Ridge.

The abundant flora of coniferous associated with *Taxodium, Typha, Nyssa, Sparganium, Taxodium, Sphagnum,* and others as well as coal accumulation (in well 850, bauxites alternate with coaly deposits) suggest that, during the Paleocene, the landscape near the Sukhoe deposit was a swampy lowland. It must be emphasized that hygrophytes were typical for local wet areas, but the climate was not humid in general. (Laukhin and Kul'kova, 1973a).

Reconstructions of past geomorphology show that, already in the Paleocene, sublatitudinal swells and depressions had been formed in the southwestern Siberian platform (Laukhin, 1973). The Sukhoe deposit was formed in a transitional zone between the Tatar uplift and the Bol'shoi Pit depression, though not in the axial part of the latter (the figure). Later, sublatitudinal, mainly neotectonic uplifts intensively dismembered the Bol'shoi Pit depression, and it is impossible to reconstruct its continuation westward of the left bank of the Enisei. Unconsolidated Cretaceous and Paleogene rocks did not record features of the pre-Oligocene (preneotectonic) relief on the left bank of the Enisei. The Bol'shoi Pit depression is also deformed in the Enisei Ridge. The swampy origin of the Sukhoe deposit suggests that, in the Paleocene, it was located in a deep part of the depression but not in the upper part of its limb, which is in a transitional zone to the swell, as it is now. For this reason, the most probable path for sea ingression was along the sublatitudinal depression beginning

from the Ket' lower courses, where the majority of reconstructions show the east coast of the western Siberian sea in the Paleocene, located 830 km to the east. This seems to be reliable, if only reconstructions of the southeastern coast of this sea are correct, and further data will not displace its position further to the east than what is currently suggested. However, the Paleocene rocks in the upper courses of the Ket' River are very poor, and the Paleocene coast line can be reconstructed more precisely only by using indirect data. Such data could be obtained by studying the Balandin, El'chim, and Kardakan bauxite deposits, situated in the Bol'shoi Pit depression of the Enisei Ridge; they have been insufficiently studied.

Some recent materials enable a more precise determination of the time of this sea ingression (?) in the Siberian platform. The study of zonal assemblages of dinoflagellates from the Ob'–Irtysh interfluvial area (Kul'kova, 1987) showed that the palynospectra, corresponding to palynocomplex 3 from the Porozhnoe locality of the Irkinei Range in the southwestern Siberian platform are older than the middle Eocene, as was suggested earlier (Kul'kova and Laukhin, 1975). Palynocomplex 3 is now referred to the terminal Ypresian–initial Lutetian (NP 12 - NP 14). According to this and new age determinations for palynocomplexes from western Siberia, the Paleogene palynocomplexes G, D, and E from the above region of the Siberian platform seem to be older than was previously believed. It is significant that they do not contain microphytoplankton or other signs of sea genesis, and that palynocomplexes G and D were distinguished for the first time at the Sukhoe deposit. Thus, we can state at least that the sea transgression, signs of which were distinguished in well 850, did not occur at the end (and probably not in the second half) of the late Paleocene.

In the northern Verkhoyansk region, microphytoplankton was found in known outcrops of rocks of Bykovskii canal and Kunga graben (the figure, points *3* and *5*). Rocks of Bykovskii canal yielded dinoflagellates *Apectodium* (*Wetzeliella*) *articulum* (O. We) Eisnack, *Deflandres phosphoritica* Eisnack, and *Isabellidinum* sp., and outcrops of Kunga graben contain *Apectodium* (*Wetzeliella*) *homomorphum* Def. et Cook and hystrichosphaerids (possibly acritarchs), according to the definition of A.F. Fradkina. Both sections also contain abundant pollen and prints of leaves (Laukhin *et al.*, 1988; Budantsev *et al.*, 1989). The deposits containing dinoflagellates and other remains of microphytoplankton are dated at the beginning of the early Eocene, according to palynologic data, or at the end of the Paleocene, according to macroflora (Laukhin *et al.*, 1988). The composition of the dinoflagellates does not contradict these results.

It should be noted that a series of sections in Kunga graben has also been studied by the palynological method. All samples here yielded a single Kunga palynocomplex. The sections expose the Kunga coal-bearing deposits; only one sample is free of coal measures. Almost all samples from this outcrop contained microphytoplankton in amounts of 0.2 - 5.6% (usually 1.2 - 4%) of the sum of pollen and spores. The palynospectra from this section are very diverse (nearly 120 taxons), and only eight taxons (*Osmunda,* Polypodiaceae, *Picea, Pinus,* Taxodiaceae, *Alnus, Tricolporopollenites,* and *Triporites*) are comparable with microphytoplankton in terms of abundance. Accordingly, microphytoplankton is one of the microfossil groups that predominate in the palynocomplex.

Microphytoplankton was not distinguished in the coal-bearing deposits, but notable amounts of pollen of *Ericales* (1 - 3 to 21%), *Myrica* (1 - 2 to 14 - 63%), *Sciadopitys, Comptonia, Nyssa* (usually about 1%, but sometimes up to 10%), and other coastal plants are characteristic of the palynospectra. In all probability, coal accumulation was of the paralic type here. The coal deposits of Kunga and other grabens in the northern Verkhoyansk region are confined to the lower coaliferous molassoids. Evidently, the continental rifting that resulted in molassoid formation was synchronous to the rifting stage in the Laptev sea shelf; using the rift, sea waters ingressed deep into the land for 300 - 400 km. The sea occupied part of the modern Buor-Khaya bay, and it spread 40 km to the west, penetrating the territory of the modern Primorskii Ridge and Kunga graben.

Rich palynospectra of the Tastakh palynocomplex were distinguished in the middle Eocene deposits of Kunga graben (the Emgend'in series; Budantsev *et al.*, 1989). The Kingdei Formation of Kingdei graben, situated westward along the latitude of Kunga graben (Grinenko *et al.*, 1989), is the early Eocene in age, although its upper beds may belong to the middle Eocene. In addition to abundant palynospectra, many leaf imprints and continental malacofauna of the lower Eocene were distinguished in these deposits, but they do not show any signs of marine sedimentation during the middle and lower Eocene. Apparently, the transgression in Bykovskii canal and Kunga graben took place approximately at the time of the Paleocene - Eocene boundary, but not in the early Eocene.

As is clear from the above data, deposits with marine microphytoplankton in the southwestern Siberian platform and its northeastern framing are significantly different in age, although they are dated at the second half of the Paleocene in both regions. Apparently, they record different transgression stages. In both cases, the maximum sea progradation was, evidently, manifested as an ingression but related to more general transgressions, which were deeper than the middle Eocene one in the studied regions. The tectonic conditions of the ingressions were different. The sea ingressed along the sublatitudinal shallow depression in the southwestern Siberian platform and along rift grabens in the northern Verkhoyansk region. It is remarkable that the transgression in the latter region coincides with a period of high sea level, probably the maximum one

during the Cenozoic, while the ingression in the southwestern Siberian platform corresponded to the relatively low (for the Paleocene-Eocene) level of the global ocean. (Haq *et al.*, 1987).

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Sergei Viktorovich Meyen and Theoretical Stratigraphy: A Tribute to His 60th Birthday

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Abstract – The research of S.V. Meyen had an outstanding influence on theoretical stratigraphy. This paper characterizes Meyen's studies on the subject of stratigraphy, stratigraphic features, stratons and their boundaries, stratigraphic classification and typification, the essence of time, and the significance of the historical approach. This paper presents the results of his studies on such fundamental principles of stratigraphy as Steno's principle, Huxsley's principle, and Meyen's principle and on the recognition of the six structural aspects of modern stratigraphy.

Key words: *Theoretical stratigraphy, stratigraphic features, straton, classification, typification, principles of stratigraphy.*

The large but modestly titled *Vvedenie v Teoriyu Stratigrafii* (Introduction to Theoretical Stratigraphy) monograph by Meyen was submitted by VINITI for publication in 1974 (Meyen, 1989).

Even though it was not presented in the most convenient way, this book has been extensively read, discussed, and cited, and it has stimulated the studies of several stratigraphers. V.V. Menner wrote extensive comments to the book and had them delivered to the author. However, the method of presentation substantially narrowed this book's circle of readers among geologists and its possibilities for usage in geological practice. I am not aware of any published response on this book except that written by myself in *Sovetskaiya Geologiya* (Zhamoida, 1977). A much later paper by Simakov (1989) was devoted to the same fundamental principles of stratigraphy. However, the book by Meyen was definitely a remarkable event. Numerous works, both Russian and foreign, whose titles begin with such words as "Fundamentals," "Problems," "Principles," "Ideas," etc., have, at best, dealt merely with the general problems of stratigraphy, only occasionally touching upon theory. Even the scope of the problems that need to be considered by theoretical stratigraphy remains obscure.

Hence, *Vvedenie v Teoriyu Stratigrafii* not only presented necessary fundamental research, but was unique. I referred to it as a treatise, i.e., a study that successively and logically presents the main principles and definitions of stratigraphy and their relationships, mutual bonds, and applications to various branches of the geosciences.

Receiving written and oral comments from his colleagues, and thinking over the book himself, Meyen planned to continue his work on *Vvedenie* ... . Unfortunately, this was not accomplished, and the book was published 15 years later (Meyen, 1989) without the participation of the author and without changes. Nevertheless, Meyen continued his studies after 1974 and published the main results in several papers.[1] The concluding and, unfortunately, last paper was *The Structure of Theoretical Stratigraphy*, which resumed his studies in this branch.

The first and most of the later works of Meyen were devoted to paleobotany. Naturally, these papers, beginning with his candidate dissertation in 1964, showed close relations to stratigraphy. Advances in determining the ages and boundaries of stratigraphic units, phytostratigraphic correlations, paleophytogeographical systematics of areas, system analysis in stratigraphy – all of these and many other problems led Meyen to the

[1] The most important papers were republished together with *Vvedenie v Teoriyu Stratigrafii* (Meyen, 1989).

conclusion that, in stratigraphy, "... it is as if an evil spirit amuses itself by playing pranks on people, extending misunderstandings and implanting a mess in their souls." These words of Van Stenberger were used as an epigraph for *Vvedenie ...* .

Both the mentality and the personality of Meyen did not allow him to ignore this "mess in the souls," and his talent and logical thinking assisted in the successful accomplishment of this prominent task: to reveal the meaning of fundamental stratigraphic concepts and principles and to refine its logic. I think this was partly stimulated by the publication of *Proekt Stratigraficheskogo Kodeksa SSSR* (The Project of the Stratigraphic Code of the USSR) (1970), in the discussion of which Meyen actively participated as a member of the International Stratigraphic Committee.

"The task of this book," Meyen wrote (1989, p. 22), "is not to establish new stratigraphic principles and methods, but rather to attempt to understand why, despite theoretical contradictions and radical changes in the concepts from one generation to another, stratigraphy has generally pursued a definite goal and generally showed appreciable achievements."

Meyen undoubtedly succeeded in accomplishing this task.

I would like to highlight the swiftness (here I cannot find a more proper word) with which Meien overcame the most complicated stratigraphic problems, theoretical among others. *Vvedenie ...* "was written within one year, in a single stroke;" anyone reading the book can feel this.

Described below are those stratigraphic fundamentals in whose development Meyen has contributed most significantly. I will focus on the most prominent discoveries and explanations of the essence and methodology of stratigraphy.

My work on this essay was a great pleasure, even more so as I agree with the overwhelming majority of Meyen's conclusions. I will not accentuate our few contradictions, which readers can find in the above-mentioned paper (Zhamoida, 1977).

Meyen devoted his works published in 1981 - 1985 that followed the first edition of *Vvedenie ...* not only to his new ideas, but also to the elucidation of some of his earlier conclusions and concepts.

The subject of stratigraphy. Since stratigraphy is an individual science, as was postulated by Meyen, it is first and foremost necessary to formulate a concept of its subject and fundamental principles.

Meyen developed no "conclusive" (in his opinion) definition of stratigraphy emphasizing that, first, "its subject is considered by some geologists to be the earth crust as a whole, or it is restricted only to sedimentary rocks by others (Meyen, 1989, p. 50). Second, "for stratigraphy to be an individual science, on the one hand, and for its subject not to be unjustly constricted, on the other, we have to admit that, without restricting itself with respect to employed features of and relationships among geologic bodies, stratigraphy considers, in certain situations, certain features and relationships to be more important, but is itself based on predetermined and not arbitrary unity relationships." Third, "the objectives of stratigraphy are primary spatial-temporary relationships between geologic bodies and those features that provide insight into these relationships" (Meyen, 1989, pp. 50 - 51).

Summarizing his concept, Meyen touched on the broad (or extended) formulation of the stratigraphic subject: stratigraphy "deals with spatial and temporal relationships among rock complexes (or geologic bodies) in the earth crust" (Meyen, 1989, p. 51), and he emphasized that he purposefully focuses not on the properties of the rocks but on their relationships.

Hence, Meyen seemed to include into the subject of stratigraphy all geologic bodies – sedimentary and igneous, layered and nonlayered – but considered, in all his works, only proper stratigraphic units, i.e., geologic bodies formed by sedimentation processes or, at least, stratum-building processes. The modified formulation of Steno's principle proposed by Meyen appears to reflect, to a certain degree, this duality in his understanding of stratigraphy.

Fundamentals of stratigraphy. One of the most prominent results of Meyen's studies was the recognition of the fundamental principles of stratigraphy, which, taken collectively, provide a necessary and sufficient basis for stratigraphic studies. He succeeded in demonstrating that, instead of the many "laws" and "principles" used by some geologists (for example, L.L. Khalfin, A.M. Sadykov, D.L. Stepanov, and M.S. Mesezhnikov), stratigraphy actually operates with three independent principles.

Meyen somewhat extended the well-known Steno's principle ("in an undisturbed sequence, each underlying bed is older than the overlaying one") by introducing a possible genetic aspect, although not requiring that the genesis of the two contacting geologic bodies be determined (Khalfin, 1969): "such temporal relationships between geologic bodies as *earlier/later* are predetermined by their primary spatial relationships and/or genetic links" (Meyen, 1989, p. 26). On the basis of Steno's principle, relationships like *lower/higher* are understood as temporal relations *earlier/later*, thus furnishing the necessary basis for the first operation of stratigraphic studies: analysis of stratigraphic sequences and, often, recognition of stratons.

Determining identical successions (homotaxis) of fossil complexes in several geologic sequences enables one to correlate those complexes that demonstrate similar relationships with others. These complexes were termed *homotaxal*. Meyen suggested using the concept of homotaxis, which was first introduced by Huxsley, to correlate complexes on the basis of not only paleontological, but any features, for example, using paleocli-

matic reconstructions, similar ordering of paleoecosystems (Meyen, 1982b), etc.

In a paper on the concept of homotaxis, Meyen wrote that "Homotaxis is not merely the similarity of certain features of members of discrete successions – it is the similar order of certain features, which belong (or belonged) to a single body or a living being" (Meyen, 1989, p. 147).[2]

Meyen named the correlation of identical successions the Huxley's principle. He did not define it but agreed with my definition (personal communication, July 3, 1982): "Stratigraphic correlation of those geologic sequences that cannot be correlated directly can be accomplished by comparing homotaxal, i.e., identical, successions of features, including ancient environments and events" (Zhamoida, 1984, p. 12). This principle provides a basis for the second operation of stratigraphic study: correlation of stratons.

Because stratigraphic features show restricted lateral occurrences, one is bound to use several features in a chronological succession. On the basis of this, which is an operation that is generally familiar to any stratigrapher, Meyen formulated the third fundamental principle of stratigraphy and termed it *the principle of chronological interchangeability of stratigraphic features.* Here, the features may be either events or their signs. Poyarkova and Poyarkov (1977) suggested terming this principle *Meyen's* principle. Later, this name was broadly accepted by Soviet stratigraphers.

Although Meyen discussed the principle and its implementation in a number of papers (Meyen, 1981, 1982, etc.), he did not render its precise definition. He did not object to my definition (personal communication, July 3, 1982): "Different, partly overlapping areal distributions and the complex character of stratigraphic features make possible their chronological interchangeability, which enables one to correlate the most significant features on intra-, interregional, and up to planetary scales" (Zhamoida, 1984, p. 13).

"Therefore," Meyen wrote (1989, p. 123), "there are only three fundamental principles of stratigraphy. The first one (Steno's principle) establishes the chronological succession of geologic bodies in a single sequence. The second, Huxsley's principle, makes it possible to correlate geologic sequences on the basis of homotaxis. Using the third principle assures the choice of one homotaxis amongst other possible ones and, if necessary, enables changes of dependent features for independent ones."

Meyen enthusiastically accepted (personal communication, October 9, 1977) the apparent and somewhat causative relations that I had noticed between the main tasks (and possibilities) of stratigraphy, as they are formulated in *Stratigraficheskii Kodeks* (Stratigraphic Code) (1977, 1992), and its above-mentioned fundamental principles.

Simakov (1989, pp. 21 - 22) noted that the system of stratigraphic principles presented by Meyen not only "provides a basis for its operational technique" but also demonstrates that "the principles themselves reflect the more general (fundamental) regularities that operated during the origin of respective geologic bodies (stratons) throughout the whole history of the biosphere."[3]

Later, analyzing numerous "principles," I arrived at the conclusion (Zhamoida, 1984) that one more fundamental principle should be formulated. Stepanov and Mesezhnikov (1972) termed this principle *the principle of the unbiased and unique nature of stratigraphic units.* Meyen wrote concerning this matter (personal communication, July 3, 1982): "First, I was surprised by the appearance of the fourth principle but understood later that it actually can be validated. Its formulation can be different. Still, something should be said concerning the uniqueness of stratons. It was only after your article that I understood the link between the fourth principle and my statement that stratigraphic procedure is not classification in its essence – and this statement had no respective principle. Moreover, this principle must be the first on the list, before Steno's principle. The logic should be as follows: (1) unique stratons are recognized in a particular geologic sequence; (2) their chronological order is established (i.e., Steno's principle); (3) the sequences are correlated on the basis of their homotaxis; and (4) if some features are laterally diverse, we can interchange them (i.e., homotaxis is used through interchangeability). Theoretically, this procedure is on the highest level of abstraction. Naturally, we do not work in exactly this manner, because we do not start at ground-zero."

The uniqueness of stratons was virtually accepted by Meyen in his submitted book of 1974, in which he explained the usage of proper names in denoting stratons.

Meyen agreed with some other geologists who claimed that "stratigraphic principles are operative throughout the whole geochronologic scale, with only the specific techniques and respective stratigraphic features changing" (Meyen, 1989, p. 102). This statement was even more clearly formulated in *Proekt Stratigraficheskogo Kodeksa SSSR* (1970) and was repeated in all later editions.

Stratigraphic features. Meyen understood stratigraphic features as any specifics features of a geologic body or their relationships that can be either observed or inferred and that ensure statements like *earlier/later* or *contemporaneous*, i.e., such specific features that can be used in stratigraphy. Due regard should be given to their lateral extension (to which they can be traced) and the ease of their identification. A certain stratigraphic feature can later be "split" into several (for

[2] Here and below, pages in Meyen's papers 1981 - 1985 are cited according to the monograph *Vvedenie v Teoriyu Stratigrafii* (Meyen, 1989) in which these papers were included.

[3] I still do not understand why Simakov applies these laws (or principles) only to the biosphere; in my opinion, this contradicts Meyen's systematic approach to the concepts of straton, correlation, etc.

example, in a rhythmical sequence). On the other hand, several features can be regarded collectively as a single combined feature.

Meyen focused his attention on the importance of the significance of stratigraphic features and justifiably noted that solving stratigraphic problems solely on the basis of the method of majority is permissible only if there are no other reliable data. Here, the significance of each feature is proportional to its special significance, i.e., to its persistency along the strike (Ibid., p. 56). He came to the conclusion that the necessary condition in determining the significance of a feature is a geosystematic reconstruction, that is, the reconstruction of those components of the ancient geosystem that correspond to stratigraphic features or else the reconstruction of those processes in the geosystems that resulted in changes in the stratigraphic features. Therewith, he noted that using cause-and-effect links is open to many hazards and recommended, first and foremost, employing archistratigraphic features. However, he included in them "not those features that must be unquestioningly followed, but those that are useful in initial stratigraphic operations (such as subdivisions and correlations)" (Ibid., p. 37). Note that this explanation is significant not only for the procedure itself, but, in addition, it reflects the essence of stratigraphic studies. Second, Meyen emphasized that features may "inevitably" be reweighed in the course of stratigraphic studies; this, however, is natural of any science.

A straton as a subject of stratigraphy. Noting that the subject of stratigraphy may be the whole earth crust or it may be restricted to sedimentary rocks only, Meyen came to the natural conclusion that "it is more convenient to employ a stratigraphic unit – *a straton* – as a subject of stratigraphy, this subject being most often used in practice" (Meyen, 1989, p. 156). This understanding of a stratigraphic subject is now recognized by the majority of stratigraphers and is accepted in *Stratigraficheskii Kodeks* (1977, 1992). "A unit of any stratigraphic scale is to be termed *straton*," wrote Meyen (Ibid., p. 27), but he understood that this statement was not sufficient.

What is a straton or a stratigraphic unit? What is an "ideal straton"? Some regard it as a geologic body showing specific lithologic and facial features, others visualize it as reflecting a certain stage in the regional geologic history or in the history of the Earth as a whole. Still others believe that there are many independent stratons, and some recognize "abstract" and "material" stratons, etc. However, even in relatively old times, "using the principles of the paleoecosytsem approach led geologists to stratigraphic reconstructions that provoked the fewest contradictions between scientists and, hence, best accounted for factual data and assimilated new information, the availability of which had not called for the revision of units" (Meyen, 1989, p. 159). The so-called "geognostic classification" of J. von Pia; recomendations for using "all features that unbiasedly reflect certain stages of earth history and the originality of these stages in its discrete parts (*Stratigraficheskaya* ..., 1956, p. 5); the complex substantiation of the straton proposed by V.V. Menner (1962); and, eventually, criteria for the recognition and the definitions of the main stratigraphic units that were cited in *Proekt Stratigraficheskogo Kodeksa SSSR* (1970) and later extended in *Stratigraficheskii Kodeks* (1977) – all of these are just the implicit usage of the paleoecosystem approach to straton definition. Meyen noted the contributions of Krasilov (1970), and Krut' (1971, etc.), who made this "latent knowledge" obvious and demonstrated their fruitfulness. Meyen's paper *The Paleoecosystem Approach* (1982) further explored this problem. Stratons of a complex substantiation have an integrated (not an aggregate) nature, because they amalgamate a series of stratigraphic features: "Such a straton reflects a certain stage in the evolution of the paleoecosystem and is not merely the filling in between arbitrarily chosen isochronous (in the geological sense) levels" (Meyen, 1989, p. 169).

At the same time, Meyen drew attention to the fact that the validation of stratigraphic units is often based not on the evolutionary stages of the paleoecosystem but on some phylogenetic stages, which are correlated with changes in the abiotic environment. He called such an approach *latent oraganismocentrism*. It is "the paleoecosystem approach that turns stratigraphy onto a causative path and topples the long-living problem of inconsistency between the evolutionary stages of various living species and the abiotic medium. These stages were recognized on the basis of ecosystems but not individual phylogenetic branches. This furnishes an incomparably more unbiased basis for distinguishing stratigraphic units and recognizing their rank" (Meyen, 1989, pp. 94 - 95). He continues that "The succession of stratons in a geologic sequence is not a combination of independent geologic bodies; it reflects stages in the evolution of a single natural body, the geosystem or ecosystem" (Meyen, 1989, p. 129).

He believed that the formal definition of an ideal straton would be presented in the future, but he listed four requirements (which he termed, for some reason, "general approaches") that need to be fulfilled: isochronous (in the geological sense) boundaries, the possibility of using the principle of chronological interchangeability of the features (i.e., the complex nature of feature), the "paleoecosystem" nature of the boundaries, and the dependence of the geographic occurrence only on the possibility of observing specific stratigraphic features (Meyen, 1982).

Stratigraphic boundaries. Stratigraphic boundaries must be, according to Meyen, of an isochronous nature: "If the diachronous nature (in the chronological sense) of a certain boundary can be proved, the boundary ceases to be stratigraphic in essence" (Ibid., p. 62). However, he considered the isochronous nature not as synchronism (chronometricly identical ages) but as

chronological coincidence, in other words, as "correspondence, correlation, and the identity of those features (reflecting environments and events) that rest on the basis of the chronological scale itself or the correlative scales" (Ibid., p. 32). Isochronous boundaries should be "distinguished using the features of the highest weight in a particular situation" (Meyen, 1989, p. 169). In fact, this is exactly the meaning of geologic synchronism, which clarifies the significance of the so-called isochronous or diachronous nature of straton boundaries.

Morphological boundaries can be clear, dividing discrete stratons, or "diffuse" in a case in which the stratons grade into one another (a transitional belt). Meyen remarked that there is neither absolute discreteness nor absolute continuinity, and different degrees of continuity and discreteness depend in practice on the choice of stratigraphic features.

Despite the introduced concept of transitional belts, Meyen did not support the so-called transitional beds and, following the well-known viewpoint of A.P. Rotai, claimed that they only increase uncertainty in the determination of stratigraphic boundaries. Even less acceptable is the suggestion of L.L. Khalfin (1970) that boundary stratons (for example, a stage) should not been included in either of the adjacent systems. This situation is most often explained by the unclear age of a sequence, a situation for which *Stratigraficheskii Kodeks* (1992, XI, p. 9) proposes special designations.

Both stratons themselves and their stratigraphic boundaries are of paleoecosystem origin. Stressing, for example, that so-called purely biostratigraphic boundaries are acceptable in abstract but not practical studies, Meyen concluded this notion with a phrase quite specific to his flamboyant language: "Biostratigraphic units always bear lithologic 'haulm,' of which only a paleontologist can abstract himself but not a stratigrapher" (Meyen, 1989, p. 152).

"Observed ('palpable' and real) geochronologic boundaries correspond to a system, usually paleoecosystem reorganizations ... These boundaries combine markers of some unique events, which can be traced in geologic space using the principle of interchangeable features" (Meyen, 1989, pp. 153 - 154).

Lateral boundaries of a straton. Krishtofovich (1939, 1945) was the first to note the existence of two types of boundaries between formations: stratigraphic and facial.[4] Unfortunately, this most significant idea did not gain due appreciation from geologists. It was only decades later that the definition of a lateral boundary, which is radically different in its nature from a purely stratigraphic boundary (Zhamoida, 1980), was included in *Proekt Stratigraficheskogo Kodeksa SSSR* (1970).

Meyen accepted lateral boundaries of stratons (in the sense of transitional facial zones) and considered them to be limits, in which chronologically interchangeable features substitute one another. He stated that lateral boundaries gave rise to Golovkinskii's law (or "principle"). Having considered this problem, he came to the conclusion that geologists accepting this "law" actually reduce the weight of lithological features to a minimum and attach maximum significance to paleontological indicators. When they *a priori* suggest that both are of similar weight, this contradicts the natural system of stratons and boundaries. The empirical Golovkinskii's law was suggested as useful for those situations in which lithological features are of little stratigraphic importance (weight). This should "caution those scientists who are excessively apt to regard lithological similarity as a criterion of chronological coincidence" (Ibid., p. 99).

It is remarkable that Meyen came to an understanding of the lithologic boundary problem after considering the spatial continuity of stratons and differentiating between actual and potential continuities.

Classification, subdivision, and systematics. Meyen emphasized that stratigraphy often not only improperly employs the concepts of classification, subdivision, and systematization (systematics), but often misleadingly considers them to be synonymous.

Following such experts in logic and linguistics as N.I. Kondakov, V.S. Tyukhtin, and some others, he defined classification as the assignment of things of a certain kind to classes (subclasses, etc.) on the basis of the most significant features, which distinguish the things of one class from others. In stratigraphy, classification results in taxonomic scales of coordinative (according to the chosen features) units (taxons).

"In subdivision, the subjects are not distributed among taxons but are subdivided into their constituents" (Meyen, 1989, p. 131). Meyen ascribed not only to subdividing the subdivision of a stratigraphic sequence into strata (stratons), but also the designing of both regional and provincial stratigraphic scales (schemes) and the recognition of geohistoric periods, that is, the construction of a universal (international) stratigraphic scale.

Meyen considered systematization as "ordering subjects of a certain nature according to their chosen features and certain interrelations. Systematization is the construction of a system" (Ibid., p. 46).

Defining the above-mentioned concepts, he came to the very important conclusion that the consecutive steps of stratigraphic studies, i.e., the entire stratigraphic procedure, "is of a synthetic nature and, being a systematization in its essence, includes classification and subdivision as necessary but sometimes independent components" (Ibid., p. 47). He attached much importance to the feedbacks between these components and systematization itself, but ascribed the leading role in all of these operations to chronological ordering.

Typification, standardization, and meronomy. Meyen remarked that the concepts of *nomenclature type* (i.e.,

[4] The latter boundary type is specific of local and regional stratigraphic units.

a name carrier) and *standard* (i.e., a possessor of specific features) are entangled in stratigraphy. This fact, as in biology, shades the relationships between nomenclature, taxonomy, and typification. Having substantiated the concepts of classification and subdivision, he invented, in addition to the unit of classification (taxon), the subdivision unit *meron* (from the Greek *meros* – part, member). The proposed new discipline *meronomy* is "the theory of a subject subdivided into constituent parts and their ordering into classes (merons) ... Taxonomy and meronomy are the two branches of *typology*, the general science dealing with the diversity of subjects" (Meyen, 1989, p. 147). Relationships between taxonomy, meronomy (including stratonomy), and nomenclature are illustrated by the following table (Ibid., p. 77):

Table showing relationships between taxonomy, meronomy, and nomenclature in stratigraphy

Distinguishing of classes and systematic units (classification and systematics)	Distinguishing of members (subdivision)	Distinguishing of stratigraphic units
Taxonomy	Meronomy	Stratonomy
Taxon	Meron	Straton
Taxonomic standard	Meronomic standard (archetype)	Stratostandard
	Nomenclature	
Nomenclature type of a taxon	Nomenclature type of a meron	Stratotype

Stratonomy is defined as a complex of features used in the stratigraphic subdivision of geologic bodies, i.e., the recognition of stratons. In other words, stratonomy is a special case of meronomy or stratigraphic meronomy. However, this generally justified understanding leads to certain misunderstandings and confusion.

In this recognition of meronomy-stratonomy, Meyen proceeded from biological subjects and biological practice, as L.S. Librovich and N.K. Ovechkin (1963) did in developing the concept of the *stratotype*. However, if biological species of a particular taxon (for example, species *Ranunculus acris*) and their parts (roots, stalks, etc.) are defined here virtually unambiguously, the subdivision of a stratigraphic sequence into stratons of different ranks, up to a member or bed, can often be performed in an absolutely different manner. Thus, Meyen deliberately emphasized that "the contents of stratons are the subject of nomenclature but not stratonomy," however, "there is also the nomenclature aspect, which is related not to typization but to priority" (Meyen, 1989, p. 78). Still, the concept of a straton cannot be comprehensively defined without characterizing its content. If so, why is a stratotype not a startostandard? I posed this question, although in a somewhat implicit form, in my article (Zhamoida, 1977) devoted to Meyen's book (1974). I do not recall whether we discussed my question, but he later admitted that such a controversy existed. Considering the significance of the stratotype, he arrived at the conclusion that "an unambiguous definition of stratons is possible solely through stratotypes (including the stratotypes of boundaries), whose function is *remarkably different* (emphasis by the author) from that of nomenclature types" (Meyen, 1989, p. 129). I do not know whether Meyen then had it in mind to change the above table by adopting a stratotype as a startostandard and considering a nomenclature type to be solely the term for holostratotype, or whether he admitted that a standard and nomenclature type can coincide.

Relationships among the categories of the main stratons. When A.G. Werner's concept of common protracted stages in earth history was published, two concepts of stratigraphy appeared, which Meyen called *universalism* and *regionalism*. The former attached priority to the units of the most general (international) stratigraphic scale.[5] The latter concept was based on regional features of sequences. Reverse relationships (which were termed *contradictions* by Meyen) between the divisibility of stratons and the possibility of tracing them along their strikes cause the variable stability and reliability of different subdivisions of the general scale. This brought about the concept of radical differences between the units of regional stratigraphic scales[6] and those of the international scale (Nikitin and Chernyshev, 1989; Khalfin, 1969; and others), to the extent that the latter was regarded as a tool for the external measurement of absolute Newtonian time or a certain nonmaterial category.

Three categories of the general stratigraphic units [local, correlative (regional), and general] were still included in the first edition of *Proekt Stratigraficheskogo Kodeksa SSSR* (1970), in which the common principles of their classification and individual nature (in contrast to the concept of the common scale) were emphasized; however, this does not mean their absolute independence (Yarkin *et al.*, 1971).

Sokolov (1971, p. 160) wrote that "The peculiarity of the general stratigraphic scale consists only in the fact that it reflects the continuous character of stratigraphic sequences (resulting from purely regional synthesis), and that it is adopted, by virtue of this fact, as an international chronostratigraphic standard". Later, Teslenko (1976) proposed that general units be considered as those integrating local units of respective ages.

Meyen came to the concept of stratons of the regional and international stratigraphic scales in a different way by demonstrating that they are principally identical in their genesis but "are different in their lateral extension and, hence, in the sets of specific features

[5] In the USSR, it was the concept of the generalized stratigraphic scale (*Stratigraficheskaya Klassifikatsiya* ..., 1956).

[6] Meyen considered local and regional units of regional scales to have the same meaning as they are given in *Stratigraficheskii Kodeks SSSR*.

that were established as their basis" (Meyen, 1989, p. 57). From this standpoint, he came to nearly the same definition that was cited by Sokolov: "In fact, the international stratigraphic scale is a succession of regional stratigraphic scales, which were selected in a special fashion" (Meyen, 1989, p. 127). He regarded attempts to prove the independence of international and regional scales as attempts to introduce the concept of absolute time in stratigraphy (see below).

The three main goals of stratigraphy, which are formulated in *Stratigraficheskii Kodeks SSSR* (1977, 1992), actually predetermined not only the distinguishing of the three categories of the main stratons but also their relationships. It is pertinent to recall once more that the main goals of stratigraphy and its fundamental principles, which were formulated by Meyen, are interrelated (Zhamoida, 1977).

This problem is directly related to his suggestion that we differentiate between the actual and potential spatial continuities of stratons. The actual, i.e., actually observed, continuity of distribution all over the Earth is not typical of any straton, but the units of the international stratigraphic scale suggest their planetary continuity or, in other words, their potentially planet-wide validity, which is possible due to the chronological interchangeability of their specific features. Such an approach ensures the assignment to general stratigraphic subdivisions of the international stratigraphic scale of not only zones, but smaller units too. This was accepted in the second edition of *Stratigraficheskii Kodeks* (1992).

Considering the relationships between straton boundaries in the international and regional stratigraphic scales, Meyen came to the conclusion that only two situations are principally possible: (1) the boundaries coincide, and (2) their relationships are unknown. I still do not understand why he ignored the third situation in which the boundaries do not coincide in the case of any possible divisibility of the general scale. But his main conclusion, which has been proved by the entire long-term experience gained by geologists, is as follows: "The coincidence of boundaries still does not mean the coincidence of stratons and, especially, of their ranks, which evidently may be different" (Meyen, 1989, p. 116). This is the essence of the independent nature of the main straton categories, among which both the local and regional stratons of a particular area reflect the specific geologic history of a certain area or the region as a whole.

Meyen proved the unity of stratigraphy not only through theoretical links between its branches and principles, but also by demonstrating that geologic sequences cannot be independently subdivided using solely their separate features. Because of this, the (1992) special stratigraphic units recommended in *Stratigraficheskii Kodeks SSSR* are considered to be auxiliary and supplemental the main units.

Time in stratigraphy. The idea pertinent to all of Meyen's works is that stratigraphy "... cannot exist without a definition of time and a consideration of temporal relationships. Its main principles, being chronological in their nature, are thus historical" (Ibid., p. 42). However, the proponents of multiple "stratigraphies" and the primary role of lithostratigraphy often try to give the impression that some categories of stratons are independent of geologic time and, vice versa, a certain "pure" chronostratigraphic category is, in their opinion, independent of any material stratigraphic basis.

Meyen emphasized that the notion being introduced at that time of *earlier/later* is an indicator of chronological (geochronological) relations in the evolution of geologic bodies, in this case, stratons. He revealed the erroneous character of the concept of absolute time in stratigraphy. This is explained by a very simple reason: there are no external (with regard to proper stratigraphic data) time scales in stratigraphy. The notion of the spatial-temporary unity of stratons "results in the discrediting and removal from theoretical stratigraphy of such notions as chronostratigraphy, chronostratigraphic units, and chronostratigraphic scales in the sense that was attached to them by H.D. Headberg and his followers" (Ibid., p. 52). I cannot help but present another citation from a later paper by Meyen: "The expression 'geological records' appeared to be remarkably precise and completely consistent with the nonclassical (non-Newtonian) concept of time. One should only be aware that, in addition to time, which is fixed in these records, a geologist does not have, and cannot have in principle, any other time to deal with" (1989, p. 127).

He emphasized the indivisible character of units of the stratigraphic and geochronologic scales, an idea that was presented much earlier by L.S. Librovich (*Stratigraficheskie i Geokhronologicheskie Podrazdeleniya*, 1954) and picturesquely formulated by A.P. Rotai (*Stratigraficheskaya Klassifikatsiya i Terminologiya*, 1956, p. 7): "Stratigraphy and relative geochronology are simply two sides of the same coin, and, thus, a stratigraphic classification cannot be separated from a geochronologic classification either in general principles or in details."

The concept of synchronism in stratigraphy was extensively discussed both at conferences and in the literature. In addition to the aforesaid, Meyen noticed that it is not permissible to mix up physical synchronism (in absolute Newtonian time) with homotaxal traces of events, which are the only material at a geologist's disposal. He understood stratigraphic synchronism as geochronological synchronism, "... which means accordance, compatibility on the basis of certain stratigraphic features, which are chronologically interchangeable" (Meyen, 1989, p. 59). Physical synchronism can provide grounds for choosing one of the homotaxal sequences (which carries features of maximum weight) using actualistic models (Meyen, 1982c). Hence, "for a stratigrapher, there are no ideal chronostratigraphic

boundaries that reflect isochronous levels irrespective of material surfaces" (Meyen, 1982c, p. 151). These conclusions remarkably elucidate the actual meaning and significance of the so-called isochronous and diachronous stratigraphic boundaries.

Proceeding from the above-cited concept of time in stratigraphy and Huxley's principle, Meyen defined breaks in stratigraphic sequences not by using time, which does not leave traces, but as "the absence of a straton (or its part), which occurs in another area. This is an absent member of one of the homotaxal successions" (Meyen, 1989, p. 126).

Historical approach in stratigraphy. Meyen devoted a special paper to particular features of historism in geology (Meyen, 1982e). In stratigraphy, this problem is related to the problems of geological periodization, biological evolution, and specific aspects of ranking stratons and geological scales themselves (the latter point was also considered earlier).

Considering, as most scientists do, historism as a tool of knowledge, Meyen focused on four common scientific principles that are particularly important for historical reconstructions, representing the subject of geology as a whole and stratigraphy in particular: the principle of typological extrapolations or the identification of a taxon or another subject based on particular members of the taxon or parts of the subject; the usage of the principle of processional reconstructions (A. Bergson), which facilitates the revelation of, for example, ontogenesis, physiology, and ecology of fossil organisms; the principle of meronotaxonomic discordance (Yu.A. Urmantsev), which implies that classes of subjects (taxons) are in a polymorphic but not isomorphic correspondence with classes of merons; and, finally, the principle of multiple working hypotheses (T. Chamberlain), the violation of which is the most common, often fatal fault of geological hypotheses, "theories," "laws," etc.

Meyen briefly touched upon five other laws dealing with historical reconstructions: three of them are pertinent to typology, and the other two determine the existence period of a subject. Meyen came to two important conclusions: (1) All of the principles are interrelated and, hence, a historical reconstruction "will always be not a single act but a recurrent, iterative procedure, which will gradually approach the coordination of available facts and empirical generalizations" (Meyen, 1989, p. 184). (2) Any historical study begins with a search for recent, observable analogies; in other words, "any historical investigation is actualistic, regardless of how well its conclusions are validated" (Krut', 1973, p. 45).

Naturally, Meyen touched (as early as in 1974, and even earlier) upon the problem of the usage of Darwin's evolutionary model or "synthetic theory" in stratigraphy. Noting that such a basis of stratigraphy as evolutionary theory is fairly unsteady (because stratigraphy should use its causative, the most controversial constituent), he drew attention to four (of many) phenomena, which are very rarely taken into account by stratigraphers. These are the parallel characters of phenotypical and modificative variability that impose significant restrictions on the validation of stratigraphic boundaries, particularly within the international stratigraphic scale, by phylogenetic interrences at the species level; still unexplainable geographic parallelism, which is sometimes mistaken for genetic relations between taxons; the possible inheritance of gained features (somatic induction); and the possibility of nongamete transition of genetic information. Meyen concluded that "the theory of evolution still has a fairly indirect bearing on stratigraphy and plays mainly an explanatory, not heuristic role." It is thus not by chance that "changes in the predominant evolutionary concepts have exerted little effect on stratigraphic studies" (Meyen, 1989, p. 97).

Meyen also touched (1982a) on the problem of historical periodization in geology and related problems of stages in biota evolution and the designing of stratigraphic scales. He assigned geohistoric periodization, which we cannot ignore but should adequately consider, to subdivision, i.e., to the field of meronomy.

However, periodization is neither universal nor unique: multiple periodizations can exist, including those in geohistory, and we must choose that which best fits the given task. Although many scientists (G.P. Leonov and some others) believe that only geologic stages of regional evolution are natural, planetary events are also known (and apparently more will be known) and, thus, certain global stages.

Recent studies on respective themes in the framework of IGCP and other projects (for example, specialized sections of IGC) demonstrate the correctness of this approach, although it mainly concerns the unit boundaries of the general stratigraphic scale.

"Stratons of regional stratigraphic scales better correspond to the geohistorical periodization of respective areas than units of the international stratigraphic scale do in respect to planetary periodization. However, even stratons of regional stratigraphic scales cannot be regarded as entirely isomorphous with the geohistorical periodization of the region" (Meyen, 1989, pp. 56 - 57). Naturally, determination of straton ranks and their grouping, "although they show many features in common with geohistorical periodization, still cannot be controlled solely by this procedure" (Ibid., p. 56). In order to obtain a hierarchy of stratons, it is necessary to work out a hierarchy of successive (in time) geosystems with due account for the stratigraphic weight of their specific features. This procedure results in stratigraphic scales, which are different from "measuring" scales (physical, etc.), because in using the former, "we cannot measure anything: rather, we arrange geologic subjects according to their relations *earlier/later* or *in between*" (Ibid., pp. 27 - 28). More detailed information on this problem can be found in the papers of Simakov (1974, etc.).

The structure of theoretical stratigraphy. Two years prior to his death in 1985, Meyen wrote a paper on, as he put it, the least explored field of theoretical stratigraphy: its structure.

He visualized the general task of a theory to be the reduction of particular situations to a restricted number of typical cases. In application to stratigraphy, this means distinguishing of the most general (interregional and global) regularities in stratigraphic features of particular local areas and regions. He stressed that stratigraphic studies are collective and interdisciplinary in their nature, and the necessity to adopt stratigraphic documents on representative conferences introduces another specific aspect: collectivization, which is not typical of most scientific disciplines.

Using a general philosophical approach, the structures of other theoretical disciplines, and an analysis of the literature, Meyen proposed that six aspects of theoretical stratigraphy be distinguished, but he emphasized the conventional nature of this differentiation, because many theoretical statements are interdependent. It is not necessary to describe these aspects in detail, and I will only list them with minimal comments.

The logic–methodological aspect encompasses a broad range of problems: the definition of stratigraphy, its objects and challenges, and projections of philosophical and gnoseological principles on this science.

The methodical aspect includes the techniques of taxon recognition supplemented with surveying and assessment of the potentials of certain methods and their interaction.

The theory of the earth stratigraphic structure (third aspect) includes the development of such concepts as the stratisphere, stratigraphic records, and typology of stratons and their boundaries.

The semiotical aspect regards the usage of symbol (sign) systems (columns, profiles, legends of maps, schemes, and scales) and stratigraphic terminology, nomenclature, and indexing.

The general task of the praxeological aspect is the analysis of a stratigrapher's work and the development of recommendations on its rationalization, including the economics of research.

Finally, the aspect of theory development comprises the consideration and comparison of viewpoints developed by different scientists and scientific schools, studies of their evolution, and the history of stratigraphy as a whole.

As Meyen noticed, there are still no studies on theoretical stratigraphy that cover all of these aspects, although many of them have been considered by V.V. Menner, G.P. Leonov, D.L. Stepanov, and M.S. Mesezhnikov.

His comprehensive viewpoint on branches (aspects and features) of theoretical stratigraphy and their logical systematization is impressive. I asked him, in my first paper concerning this work, whether it would be correct to excessively extend the concept of theoretical stratigraphy. He answered: "I do not think we should be afraid of excessive extension of the theoretical sphere. I believe any statement made in a general form, so to say 'with the indefinite article,' is theoretical. If something does not fit the theoretical consideration, OK. It is never too late to restrict. But to overlook something is much more dangerous, because in this case, people will act according to the *ad hoc* principle, and the theory will give way to prejudices under the guise of common sense" (personal communication, June 29, 1986).

As is evident from this his comments above, Meyen planned to continue these important studies, but fate decided differently.

In the conclusion of this section, I have to add a few words about the evolution of Meyen's thoughts concerning stratigraphic codes. During the discussion on projects of *Stratigraficheskii Kodeks* (1970, 1974), he believed that this code, like biological codes, must include only a direct hierarchy of stratons and the rules for their terminology. Experience gained by Soviet and foreign stratigraphers in using stratigraphic codes convinced him that their contents have to be extended. He wrote in the above-mentioned paper: "If biological codes bear a predominantly semiotic meaning, stratigraphic codes gain the sense of a general theoretical manual, which reflects different aspects of theoretical stratigraphy" (1989, p. 192).

Upon considering the nearly unbounded broad spectrum of Meyen's studies and his profound contribution to theoretical stratigraphy, I will try to highlight the most important aspects:

(1) He distinguished and provided largely new validation of the three fundamental principles of stratigraphy, one of which was termed Meyen's principle.

(2) He developed the first complete structure of theoretical stratigraphy.

(3) He formulated the concepts of *meron* and *meronomy*, determined their differences from the concepts of *taxon* and *taxonomy*, and applied the former to stratigraphy.

(4) He introduced into stratigraphy such concepts as *stratigraphic feature, weight of a feature, virtual and potential spatial continuity of a straton*, etc.

(5) He revealed the geologic sense of the concepts of *time* and *synchronism* in stratigraphy and of the isochronous nature of straton boundaries; he also innovated the concept of *chronological interchangeability of features*.

(6) He substantiated the specific features of historism and historic reconstructions in stratigraphy.

Meyen also significantly contributed to the exploration and understanding of other problems, first and foremost, to the validation of the individuality of stratigraphy as a science and to the concept of the geo-

system nature of stratons and the understanding of its lateral boundaries.

His theoretical works, most of all the aforementioned monograph, always showed direct links with geological practice. This includes, among other things, the enumeration and explanation of the most common stratigraphic errors, to which Chapter 18 of the book is devoted.

When this essay was two-thirds completed, I received, from Margarita Alekseevna Meyen, a copy of a few pages from Meyen's manuscript, which he called *Light and Shadow*. These were the pages devoted to the book *Vvedenie v Teoriyu Stratigrafii*. Meyen recounts how he decided to write the book, how the book was written, and tells of responses to his previous reports on this theme and the book itself.

These memos confirmed my speculation, which I mentioned at the beginning of this essay, that the book was actually written "in one stroke." Here are fragments from his notes: "For me, 1973 was the year of theoretical stratigraphy ... In March, I reported to the Scientific Council of the Geological Institute on the principles of stratigraphy. But the title of the report was 'On Stratigraphic Subdivision' ... I spent the whole first half of 1973 thinking over the wealth of stratigraphic concepts, definitions, procedures; I tried to synthesize a single theoretical construction of all this. I read and thoroughly analyzed books ..., wrote numerous synopses and many memos. Extensive material had accumulated by the summer ... (In late September - early October, the Meyens spent their vacation in the Nikitskii Botanical Gardens; comment of M.A. Meyen). Thus, I decided to use this spare time and my brain. I decided to write down all that I had accumulated on stratigraphy. Since all this had been thought over and discussed many times, my progress was fast. I composed the general logical plan of the book, prepared drafts by chapters, and began writing. The manuscript literally ran out of my hands, page by page. I began it on October 3 and resumed writing in Moscow; I had written half of the book by the New Years holidays and finished it on February 16, 1974."

Meyen liked his book, although he later noted a few flaws. In his own words, he regarded the book as "the first theoretical guide to stratigraphy based on a limited number of logically interrelated principles, which are synthesized into a single, logically bound construction" (here and below, citations are from these notes).

As I mentioned at the beginning of this essay, the book was actively and broadly discussed and used, despite the inconvenient form of publication. But how was it met? This is not a simple question and, to judge from the cited notes, this naturally distressed Meyen.

He wrote concerning the above-mentioned report: "I do not remember exactly how my report was met and which questions were asked, I just felt it was generally declined." Three other phrases from the same manuscript are as follows: "I faced, almost immediately, contradictory opinions." "Some geologists tried to do more than just study the book, and they tried to absorb not only its contents, but also its spirit, to use it in their work." "This is only one side of how it was met. On the other hand, there were diverse misunderstandings ... The book was actively confronted by some geologists and stratigraphers who dealt with mathematics and worshipped the ideals of logical positivism ... My principles were nothing, in the opinion of these people, such as my concept of time. In other words, I had found no points to contact them. Still, all the criticism ... was a form of respect."

I hope that the readers feel that I not only met the works of Meyen with great interest, but also sincerely respected and even admired him. His words, which were very bitter for him, though not unpleasant for me, written on the reprints of my papers I sent to him, were as follows: "Looking attentively through them, I was pleased to see again how similar our opinions are. I think I agree with you more than anybody else" (personal communication, February 17, 1980). He wrote two and a half years later from the hospital: "I always regarded you to be the only one who understands what I am speaking and writing about. It is very pleasant, but still you are the only one" (personal communication, July 3, 1982).

Naturally, I was not "the only one," maybe his contacts with others were just not as close. He surely understood that there cannot be many scientists interested in theoretical problems, but he believed that "sooner or later, the circle of those interested will remarkably widen, as it was with theoretical biology" (personal communication, July 14, 1974).

In theoretical stratigraphy, he was far ahead of both his colleagues and his time. Further development and exploration of works accomplished by Meyen in theoretical stratigraphy is the subject of subsequent studies by his followers. Let us hope this will be performed in the nearest future.

Reviewer B.S. Sokolov

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CHRONICLE

Recent Achievements in Upper Paleozoic and Mesozoic Biostratigraphy of the Tethyan Region[1]

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The *Shallow-water Tethys 4* International Symposium was held on September 8 - 11, 1994, in Albrechtsberg, Austria. Three previous symposia on this theme were held in Italy, Australia, and Japan, respectively. The symposium was organized by the University of Vienna. The participants were 80 scientists from 19 countries: Australia, Austria, Bulgaria, Great Britain, Hungary, Germany, Iran, Italy, Canada, China, Russia, Romania, the Slovak Republic, the USA, Taiwan, the Czech Republic, Switzerland, and Japan. The majority of scientists came from western Europe. In total, 57 papers (including 18 posters) were presented at the symposium.

After an opening speech by E. Kristan-Tollmann (University of Vienna), Chairwoman of the Organizing Committee, A. Tollmann (University of Vienna) gave an introductory lecture on the Tethyan region.

The majority of papers were devoted to problems of Permian-Triassic biostratigraphy as well as to paleobiogeography, paleoecology, and tectonic models. K. McKenzie (University of Melbourne) paid special attention to the Tethyan paradigm, considering the ideas of Suess. The geology of pelagic cherty deposits containing Permian radiolarians was considered by I. Ezaku and K. Kuwahara (Osaka City University). In his paper, Yang Zunyi (China University of the Geosciences) referred to problems of Permian stratigraphy in southern China. K. Ueno (University of Tsukuba) cited new data on Permian fusulinids from southwestern Japan, while H. Yu (University of Nanking) adduced new materials on the Upper Paleozoic deposits of continental China. A.M. Popov (Far East Geological Institute, Vladivostok) reported new data on well-preserved Paleozoic Rhyniaceae from the Primor'e region. These new finds contribute greatly to the knowledge of ancient continental flora development. Of particular interest was a paper by M. Orchard (Geological Survey of Canada), which was devoted to the taxonomy of conodonts from Permian–Triassic boundary deposits. In Orchard's opinion, the current data are not sufficient for attributing the *Otoceras* Beds to the Permian, because they lack the Changsi conodont assemblage of *Neogondolella changsingensis–N. deflecta*. Transgressive conodont assemblages from Lower Triassic deposits of the Pacific belt and Tethyan region and their correlation were also considered by R.K. Paull and K.A. Paull (University of Wisconsin). They relate the development of the conodont assemblage with *Hindeodus typicalis, Hindeodus parvus, Isurcicella isarcica,* and *Neogondolella carinata* (the latter was recorded in deeper facies) to the Griensbachian transgression, and the assemblage with *Neospathodus waageni* and *N. pakistensis* was attributed to the Smithian transgression. The Spathian transgression was responsible for the development of *Neogondolella jubata*; *N. homeri*; and, to a lesser extent, *N. triangularis*. This problem was also discussed in the paper by A. Baud (University of Lausanne). E. Kristan-Tollmann (University of Vienna) shed light on the position of the boundary between the Tethyan and Pacific regions. Yin Hongfu (China University of the Geosciences) considered the major Triassic geologic and biotic events in the eastern part of Asia. Yu.D. Zakharov (Far East Geological Institute, Vladivostok) devoted his paper to the problems of defining the Induan–Olenekian boundary. He proposed stratotypes for these stages and substages in Chidru and in the Buur-Nyykabyt and Mengilyakh localities of the Solenyi Range and Yakutia, respectively. He also proposed an Induan–Olenekian boundary stratotype in the Tri Kamnya Cape area in the southern Primor'e. In the latter, the base of the Olenekian Stage is defined by the first occurrence of ammonoids of *Hedenstroemia* genus. New data on Triassic foraminifers of the Crimea-Caucasus region were cited in the paper by V.Ya. Vuks and G.P. Pronina (Russian Research Geological Institute). In their communication, K. Budurov and E. Trifonova (Geological Institute, Bulgarian Academy of Sciences) suggested zonal scales for different types of sequences in the eastern Balkan region, based on their recent studies of Triassic conodonts and foraminifers. Carbonate sedimentation patterns typical of the Middle Triassic were considered in papers by Y. Michalik and D. Rehakova (Geological Institute, Slovak Academy of Sciences) and by M. Boni, A. Lannace, A. Climaco, and V. Zamparelli (University of Napoli, Italy).

[1] Proceedings of the International Geological Symposium, *Shallow-water Tethys 4,* in cooperation with a meeting of the Triassic Subcommission of the International Stratigraphic Commission and with workshops of working groups on the Permian–Triassic boundary and on Project 359: "Correlation of the Permian–Triassic in the Tethyan Region, Circumpacific Belt, and Gondwanan Margins."

The problem of the position of the Triassic–Jurassic boundary and the selection of this boundary stratotype was discussed by G. Warrington from the British Geological Survey. M. Tamura (University of Kumamoto, Japan) listed new data on Tethyan bivalves from the Upper Triassic of Japan and showed their importance for paleozoogeographic reconstructions.

Several papers were devoted to the biostratigraphy of the Jurassic, Cretaceous, and Cenozoic and to certain aspects of paleogeography and mathematical simulation.

Meetings of the related International Comissions took place in association with the symposium.

At the meeting of the Triassic Subcomission of the International Stratigraphic Comission, A. Baud reported on the activity of this subcommission and its working groups on the Permian–Triassic and Triassic–Jurassic boundaries and Triassic continental deposits. Considering the forthcoming elections in Beijing, he proposed M. Gaetani (University of Milano) as his successor to chair the subcommission. In his report on the activity of the working group (Project 359 of IGCP), Yin Hongfu stressed that selection of the Permian–Triassic boundary stratotype was the principal problem considered during the International Permian Symposium held August 28 - 31, 1994, in China. The section in the Meishang locality (southeastern China) was suggested as this stratotype sequence. The final decision will be made according to the votes of every member in this working group.

Scientific sessions were preceded by geological excursions to classical sequences of the Upper Paleozoic and Triassic of the Carnian Alps and to the Upper Triassic, Jurassic, and Cretaceous sections of the Northern Alps (Salzburg and Tirol). Postsymposium excursions were conducted in the Salzkammergut area of the Northern Alps, where Triassic deposits are widespread.

The symposium summed up the latest achievements in the biostratigraphy and paleobiogeography of the Upper Paleozoic, Mesozoic, and lower Cenozoic of the Tethyan region and adjacent territories. Participants of the symposium became acquainted with the modern mathematical methods applied in geology and related branches of science. The symposium also outlined the prospects for international scientific cooperation. It was agreed that the next symposium, *Shallow-water Tethys 5*, will be held in Bangkok in 1997, and the next meetings of the working group on Project 359 of IGCP are to be held in Hanoi in 1995 and in Beijing in 1996 (within the bounds of the regular IGC session).

Reviewer M.A. Semikhatov

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